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**Evaluation of Safety and Development of
Guidelines for Protected/Permitted Left-Turn
Signal Controls**

March 2009

**Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712**



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EVALUATION OF SAFETY AND DEVELOPMENT OF GUIDELINES FOR PROTECTED/PERMITTED LEFT-TURN SIGNAL CONTROLS

FINAL REPORT



Prepared for
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ABSTRACT

This research addresses two particular issues associated with protected/permitted left-turn signal controls: the safety of a special protected/permitted left-turn control/display implemented at several intersections in the Las Vegas area, and the selection of appropriate left-turn control types. The safety of the special protected/permitted left-turn control was evaluated based on the crash statistics from before-after implementation of the special left-turn control. Guidelines were developed using a multiple attribute decision-making approach to determining left-turn control types. The guidelines were tested in a case study based on intersections selected from three major transportation agencies in the State of Nevada.

Results from the before-after safety analyses did not reveal any obvious safety concerns about the special protected/permitted left-turn display. However, the crash data was drawn from a very small sample size, thus additional analyses may be necessary to enhance the research findings and conclusions. The additional analyses may require more observation years for the “after” period to increase the sample size, or the analyses may be conducted from other perspectives such as surveying drivers’ understanding of the special display. The left-turn control guidelines developed in this research are sensitive to the weighting-and-scoring scheme employed in the guidelines, which can be modified to tailor agencies’ specific policies. Based on the results from the case study, the current weighting-and-scoring scheme included in this report tends to favor a more restrictive control policy when both protected/permitted control and protected control are plausible; therefore a protected control is more likely selected. Such a difference in policy was clearly shown among the three agencies in Nevada, where the City of Reno adopts a more restrictive control policy while the City of Las Vegas adopts a less restrictive policy. The City of Sparks, however, adopts a somewhat moderate policy.

Key words: left-turn control, guidelines, crash analysis, safety, multiple attribute decision making, protected, permitted

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EXECUTIVE SUMMARY

There are three common types of left-turn controls at signalized intersections, namely permitted, protected only, and protected/permitted. This research addresses two particular issues associated with protected/permitted left-turn signal controls: the safety of a special protected/permitted left-turn control display (referred to as the Las Vegas LT Display) implemented at several intersections in the Las Vegas area, and selection of appropriate left-turn control types. The Las Vegas LT display provides an innovative solution for both efficiency and safety. The project involved the following two major research objectives: (1) evaluation of the safety aspect of the Las Vegas LT Display through before-after studies, and (2) development of guidelines for selecting left-turn signal control types for the State of Nevada.

To achieve the first objective, crash statistics were collected at the study intersections before and after the Las Vegas LT Displays were implemented. Due to the availability of after period accident data when the analyses were performed, a two-year analysis period was used for conducting the before-after analyses. To achieve the second objective, new guidelines with a spreadsheet were developed using a multiple attribute decision making approach, which addresses one of the major shortcomings of previous guidelines that rely on single dominant factors. The research resulted in the following major findings, conclusions and recommendations.

Left-turn Control Guidelines

Findings:

- The multiple attribute decision making approach seems to be promising for developing guidelines for selecting left-turn signal control types. It overcomes one of the major shortcomings of previous guidelines by weighting various factors, arriving at decisions that align with typical engineering practices.

- The guideline spreadsheet presented in this study is sensitive to the weighting-and-scoring scheme built into the spreadsheet. The weighting-and-scoring scheme should reflect agency policy and engineering judgment. The research found different local policies such as those emphasizing safety over efficiency (more conservative) or vice versa. Such a difference in policies was clearly shown in the case studies. Therefore, the weighting-and-scoring scheme should be modified to interests of the agencies.

Recommendations:

- It is recommended that Nevada agencies utilize the guidelines and spreadsheet based on a weighting-and-scoring scheme consistent with local policy. The spreadsheet guidelines should be continually refined based on field applications.

Safety Aspects

Findings:

- The study intersections involved a small number of crashes before and after installation of the Las Vegas LT Display. At most of the locations, the Las Vegas LT Display only operated during a small portion of a day (typically the peak-periods). As a result, the number of crashes was very small. Based on this limited data, the various analyses did not reveal a significant increase in crashes after the Las Vegas Left-turn (LT) Display was implemented.
- The traffic volume data were available only at six intersections for the analysis periods in which the left-turn crash rates could be calculated. These six intersections yielded an average of 0.45 crashes per million entering vehicles. This average crash rate was the lowest compared to the crash rates reported in previous studies in which the MUTCD (Manual on Uniform Traffic Control Devices) compliant left-turn displays were used.

Conclusions:

- Based on the results from various analysis methods, it can be concluded that the Las Vegas LT Display does not exhibit any obvious safety concerns when compared to the MUTCD standard protected/permitted left-turn displays. Therefore, Nevada agencies should continue prudent use of the Las Vegas LT Display.
- To increase the sample size, it would require crash statistics be collected over a longer period of time. In addition, alternative evaluation tools may be beneficial to truly evaluate the safety performance of the Las Vegas LT Display. For example, instead of totally relying on crash statistics which are highly random in nature, surveying of drivers' understanding of the Las Vegas LT Display or conducting field observations of drivers' behavior would provide additional useful information. In addition, at least 3 years of crash data may be collected and used for a before and after evaluation.

1.0 INTRODUCTION

There are three common types of left-turn controls at signalized intersections, namely permitted, protected only, and protected/permitted. With a permitted control, the left-turn vehicles can make the turn during the normal green ball display and must yield to the opposing through traffic. Protected-only left-turn control provides a separate signal phase for the left-turn traffic with the display of a green arrow. The left-turn vehicles can only make a protected turn when a green arrow is displayed. Protected/permitted control is a combination of permitted and protected controls where the left-turn traffic receives two sequential displays: a protected green-arrow and a permitted green-ball (circular green). Depending on the phasing sequence, protected/permitted control may exist in the form of protected/permitted (i.e., a green arrow followed by a green ball) or permitted/protected (i.e., a green ball followed by a green arrow).

Historically, traffic engineers have applied one of three left-turn controls to accomplish intersection goals. As a general rule, the least restrictive form of traffic control is best. That is, traffic engineers should consider permitted control first and move to more restrictive control types as needed. For example, permitted control can be used at intersections where the travel speed is low (say less than 45 mph) and the opposing through traffic demand provides sufficient available gaps needed to make a safe turn. The example left-turn movement would need to be protected if the left-turn demand is high or if there was the possibility that unsafe turns might be attempted. Protected control is the safest control compared to permitted control. However, protected control will, under low volume conditions, generally reduce intersection capacity and increase vehicle delay, especially in urban applications.

Protected/permitted control provides a time interval where the drivers can make a left-turn under the safety of a protected control, and then during the same signal cycle there is a time interval during which the driver can make the left turn if there is an available gap in the opposing traffic. Protected/permitted control is used to provide a unique combination of safety and efficiency. Protected/permitted control is used at approximately 30 percent of all signalized intersections in the United States (1).

One issue related to protected/permitted left turn control arises when standard MUTCD protected/permitted left-turn displays are employed in conjunction with lead/lag or dual-lag left turn phasing. This condition creates the so-called *yellow trap* phenomenon (1). A yellow trap occurs when the permitted green ball of a protected/permitted left turn display terminates, and the left turn drivers waiting to make the turn mistakenly think the opposing through movement phase is terminating simultaneously. This causes a *trap* situation for the left turn drivers, potentially causing a collision with opposing through vehicles still receiving a green indication. Because of these concerns, lead/lag left turn phasing is generally precluded at intersections where protected/permitted left-turn control is used. Without using the lead/lag signal phasing, high quality traffic progression may not be achieved (2). One of the important tasks for traffic engineers is to select the best control type based on a site's specific conditions.

In order to take advantage of protected/permitted left-turn control while still allowing the use of lead/lag phasing, three alternative solutions have been exercised in practice. The first solution is to use the *Dallas Display*. Dallas Displays apply signal indication shielding (louvers) and special intersection control circuitry to control what indications are visible to the left-turn driver. More specifically, the Dallas Display prevents the leading left-turn traffic from seeing the circular yellow clearance display when the adjacent through phase displays a circular yellow indication (3). *Dallas Display* has only been utilized by a few jurisdictions.

An evolving new standard for protected/permitted left turn control is the application of the *flashing-yellow-arrow* design. The flashing yellow arrow design is the product of the NCHRP 3-54 project (4). The flashing yellow arrow design continuously displays a flashing-yellow-arrow during the permitted left-turn phase and, if applied correctly, will eliminate the yellow-trap condition.

The third solution is the so-called *Las Vegas LT Display*, which involves a protected left-turn display for the leading left-turn phase during certain times of the day (normally the peak period) to eliminate the *yellow-trap* condition. During the protected left-turn

phase, the green ball and yellow ball sections are blacked out (no display). This type of left-turn control is currently used at 10 intersections in the Las Vegas area. The details of the Las Vegas LT Display will be discussed in the next section.

The motivation of this research project stemmed from the Las Vegas LT Display. Because the Las Vegas LT Display deviates from standard MUTCD protected/permitted left-turn control displays, there are concerns about drivers' understanding of the display, thus may cause potential increase in traffic crashes at the intersections. In general, there is also a lack of national guidelines for selecting protected/permitted left-turn controls. Therefore, the project involved the following two major research objectives:

- evaluate the safety aspects of the Las Vegas LT Display, and
- develop comprehensive guidelines for selecting left-turn control types based on conditions in Nevada.

The remainder of this report is organized as follows. Section 2 provides detailed descriptions of the Las Vegas LT Display. Section 3 is the summary of the literature review and a national survey regarding left-turn control guidelines. Section 4 includes the details of the new guidelines developed in this research. Section 5 includes the detailed analyses of the safety aspects of the Las Vegas LT Display. Section 6 provides a summary of the major findings, conclusions, and recommendations. Section 7 discusses implementation issues. Finally, appendices containing works cited and other related information are attached.

2.0 THE LAS VEGAS LT DISPLAY

The Las Vegas LT Display uses internal signal controller logic to implement a protected-only left-turn control for the leading left-turn phase. It uses a standard MUTCD five-section protected/permitted signal display and operates on a time-of-day basis. This is basically accomplished by suppressing the green and yellow balls in the five-section display so that left turn vehicles are only shown the green and yellow arrow indications, followed by the red indication, whenever protected-only operation is

desired. The preferred installation of this display is to have the typical red ball at the top replaced with a red arrow; however, at this time, the MUTCD does not allow a yellow ball to be terminated with a red arrow as would be observed when the permitted turn terminates. The use of a red arrow makes it clear that this display is not a shared display, but an exclusive display for the left turn movement. The addition of a R10-21 sign (Figure 1) adjacent to the display is also recommended for added clarity. Implementing the controller logic by time-of-day and by phase avoids the *yellow trap* situation, which would normally occur while running lead/lag phasing with the standard MUTCD protected/permitted left-turn display.



R10-21

Figure 1 MUTCD R10-21 Sign for Protected/Permitted Left-turn Display

Figure 2 and Figure 3 are pictures of signals using the Las Vegas LT Display. As shown in both figures, the green ball and the yellow ball are dark while the through movements have the green ball indication, which becomes a protected-only leading left-turn phase. Table 1 further illustrates the contrast between the Las Vegas LT Display and the standard protected/permitted left-turn display conforming to MUTCD standards. The contrast is illustrated for each signal interval, where the Las Vegas LT Display has a lead/lag phasing sequence and the MUTCD display has the normal dual left-turn leading sequence. When the leading left-turn phase terminates as shown in Interval 3, the Las Vegas LT Display shows a red arrow and there is no green ball display,

indicating a protected-only operation. However, with the MUTCD display, a green ball is displayed, indicating a permitted left-turn operation.

There are ten intersections in the Las Vegas area that are using the Las Vegas LT Display, operating on a time-of-day basis. *Appendix B* has the details of the controller logic and wiring requirements to implement the Las Vegas LT Display.

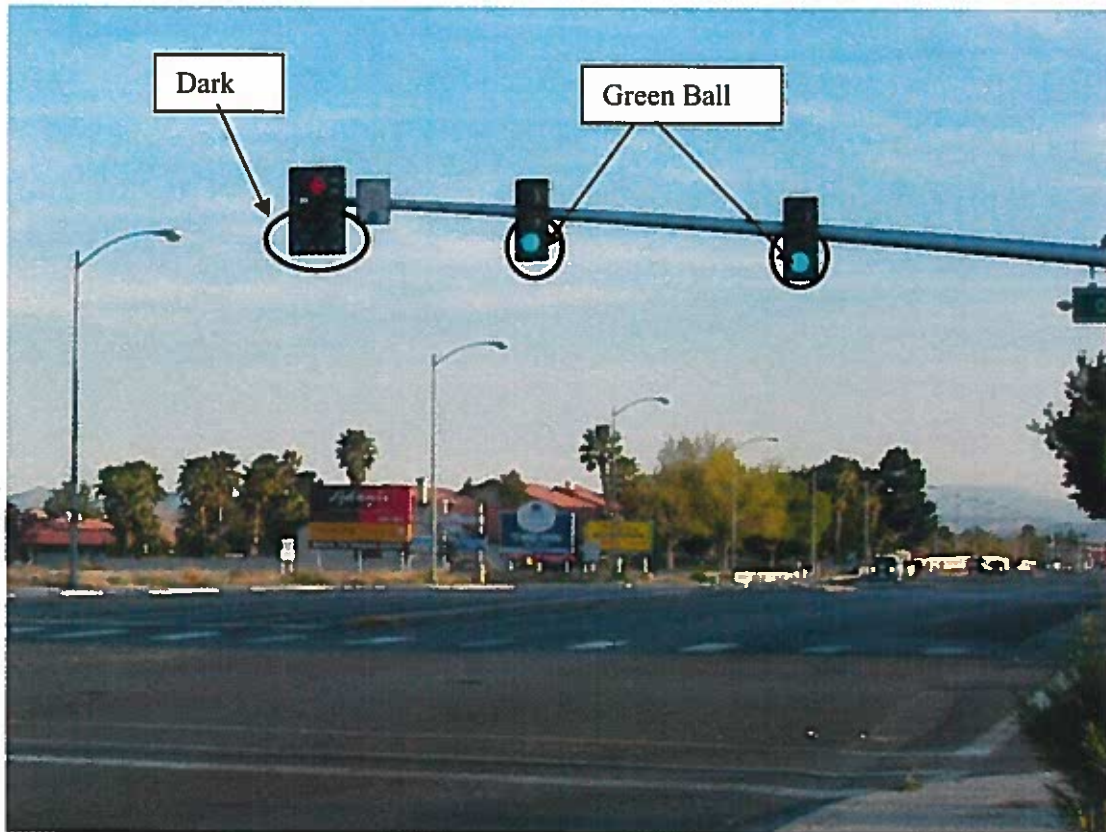


Figure 2 Red Arrow following the Yellow Arrow



Figure 3 Louvered Red Ball following the Yellow Arrow

Table 1 Contrast between the Las Vegas LT Display and the Standard MUTCD Protected/permitted Left-turn Display

Interval	Standard MUTCD PPLT Display			Las Vegas Display		
	Description	Protected/ Permitted Left Turn	Adjacent Through	Description	Leading Protected Left Turn	Adjacent Through
1	Protected leading left turn			Protected leading left turn		
2	Clearance interval for protected left turn			Clearance interval for protected left turn		
3	Permitted left turn phase begins following the protected phase			Red arrow or louvered red ball ends protected left turn phase		
4	Clearance interval for permitted left turn			Red indication remains lit through normal permitted left turn phase		
5	Red indications on the approach during conflicting cross-street phase			Red indications on the approach during conflicting cross-street phase		

3.0 LITERATURE REVIEW

This section provides a literature review of previous studies related to left-turn signal controls, with a particular focus on the guidelines for the safety aspect of protected/permitted left-turn controls.

3.1 Guidelines for Protected/Permitted Left-Turn Controls

3.1.1 Published Papers and Reports

There has been a number of research efforts conducted over the past 20 years, most of which were conducted in the 1980s, to address left-turn control issues. Various guidelines have been developed regarding the selection of left-turn control types. Two scenarios are generally involved while selecting a left-turn control. The first scenario determines the left-turn control needs for a future intersection to be constructed, while the second scenario considers appropriate modifications to existing left-turn control at an intersection already in place. For the first scenario, the selection of left-turn control should be based on a two-step process. The first step is to determine whether permitted left-turn control would satisfy the safety and operational objectives. If not, the second step is to determine whether protected/permitted or protected only control should be used. For the second scenario, left-turn crash or traffic conflict data is also considered in the decision process.

An earlier study by Asante et al. (5) resulted in the guidelines by the Institute of Transportation Engineers (ITE) for permissive only control versus controls with some protection (i.e., protected only or protected/permitted). The ITE guidelines are included in the Traffic Engineering Handbook (6) and have gained wide acceptance by many jurisdictions. Various studies have also been conducted and guidelines have been developed regarding selection of protected/permitted versus protected only control (6, 7, 8, 9). A recent study by ITE's Traffic Engineering Council (10) established national guidelines for the use of protected/permitted vs. protected only left-turn control. The guidelines were primarily developed based on earlier studies, but incorporated the results from a comprehensive survey of over 100 agencies in the United States and other

countries, including Canada, the United Kingdom, and Greece. In addition to the published guidelines, some agencies have also developed in-house guidelines. Three such in-house guidelines (11, 12, 13) obtained through the agency survey in this project are also included in the review.

In general, the guidelines by ITE (6) for permitted left-turn control have gained wide acceptance by traffic engineers and jurisdictions. It is with the protected/permitted versus protected-only controls that practice and policies vary. The difficulties involved in selecting protected/permitted versus protected-only are mainly due to balancing tradeoffs between safety and efficiency. First of all, studies have shown that protected/permitted control generally involves a higher number of left-turn crashes than protected-only. However, studies have also found that protected/permitted reduces the number of rear-end crashes and the total number of crashes almost remains the same as in the case of protected-only control (14). On the other hand, protected/permitted can normally reduce vehicle delays by 30%, especially during the off-peak periods. Reduction in vehicle delays implies reduced user costs, which is the main reason why the general public prefers protected/permitted control. Furthermore, protected/permitted control provides additional flexibilities in having varied time-of-day operations through detector design and advanced controller features (15, 16).

Major factors typically considered in various left-turn guidelines include: speed, the number of left-turn lanes, the number of opposing through lanes, sight distance, crash history or observed left-turn conflicts, left-turn demands or the product of left-turn volume and opposing through volume, capacity and delay. Engineering judgment has also been emphasized in most guidelines.

A common characteristic of existing guidelines is that the decision of which left-turn control to use is usually governed by a single factor. A threshold value is generally established for each factor, and a control type is determined once a threshold is met by a controlling factor. Below is a summary of the factors and the ranges of the threshold

values used in various guidelines for selecting protected/permitted vs. protected-only controls.

- **Speed:** All the published guidelines use 45 mph as the threshold above which protected only control shall be used. Only the two in-house guidelines by City of Toronto and FAST in Las Vegas use speed thresholds higher than 45 mph. Toronto uses 50 mph (80 kph) and FAST uses 55 mph.
- **Number of left-turn lanes:** All the published guidelines use one as the threshold above which protected only control shall be used.
- **Number of opposing through lanes:** The majority guidelines use two as the threshold above which protected only control shall be used. Using three through lanes as the threshold was found in the guidelines by Koupai and Kothari (10) and the guidelines by FAST in Las Vegas (11).
- **Sight distance:** Sight distance is determined based on the 85th percentile speed of the opposing through traffic; however, three guidelines (7, 12, 9) use the stopping sight distance, one guideline (10) uses the sight distance required for left-turn crossing with a critical gap of 5.5 sec, and one guideline (11) states both should be checked.
- **Crash history:** The majority of the guidelines use left-turn related accident frequency ranging between three accidents per year to five accidents per year, above which protected/permitted control shall be replaced by protected-only control. Some guidelines (8, 9) also use accident rate expressed as accidents per million entering vehicles.
- **Left-turn volume:** The majority of the guidelines use the cross product of left-turn volume and opposing through volume (8, 10, 11, 12, 9), although some guidelines also use the left-turn volume along (5, 12). Protected only control shall be used if the cross product exceeds 150,000 for one opposing lane or 300,000 for two opposing lanes. When left-turn volume is used, protected-only control shall be used if the left-

turn demand exceeds 300 vph (12), or 200 vph if the percentage of heavy vehicles exceeds 2.5% (5).

3.1.2 Agency Survey

As part of the research project, a comprehensive survey was conducted among agencies throughout the country to address the various issues related to left-turn controls and operations. The original survey included a total of 15 questions, covering a broad range of topics which could provide useful information for the project. The survey was posted on the internet on March 30, 2006, and a total of 36 responses were received by May 30, 2006. The 36 responses represent nine state DOTs (including Arizona, Maryland, Michigan, Louisiana, New Jersey, Missouri, Washington, Utah, and Oregon), as well as local public and private transportation organizations. *Appendix C* includes the original survey form and questions, survey responses, and a complete list of the agencies and their contact information. A brief summary of the surveyed questions and agency responses is provided next.

Agency Use of Guidelines for Left-Turn Controls

When asked whether specific guidelines are used in determining the type of left-turn controls, the majority of the agencies responded that they follow some guidelines. These guidelines could be nationally published procedures such as ITE and the MUTCD, policies developed for internal use, or based on rule of thumb. Almost all the state DOTs that responded have developed internal-use guidelines which were primarily adopted from the published national guidelines with modifications to address the state's unique features. At the local agency level, simple rule of thumb was often used, such as engineering judgment, cross product of left-turn and through traffic volumes, and safety concerns.

Important Factors for Determining Type of Left-Turn Controls

This question was designed to investigate the factors used in determining left-turn control types and their degrees of importance. It was asked to rank the following factors

based on the level of importance: crash records, traffic progression, capacity and delay, costs, citizen complaints, size of intersection, travel speed, and others to specify. Figure 4 shows the percentage of responses that placed the highest rank (#1) to each of the factors.

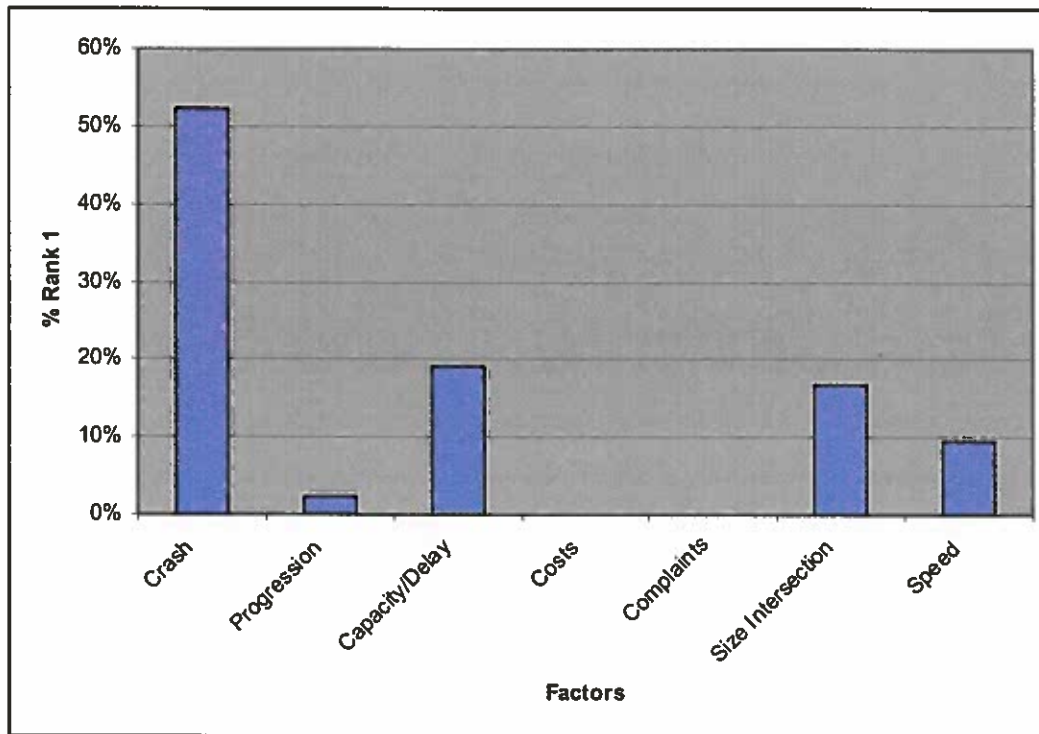
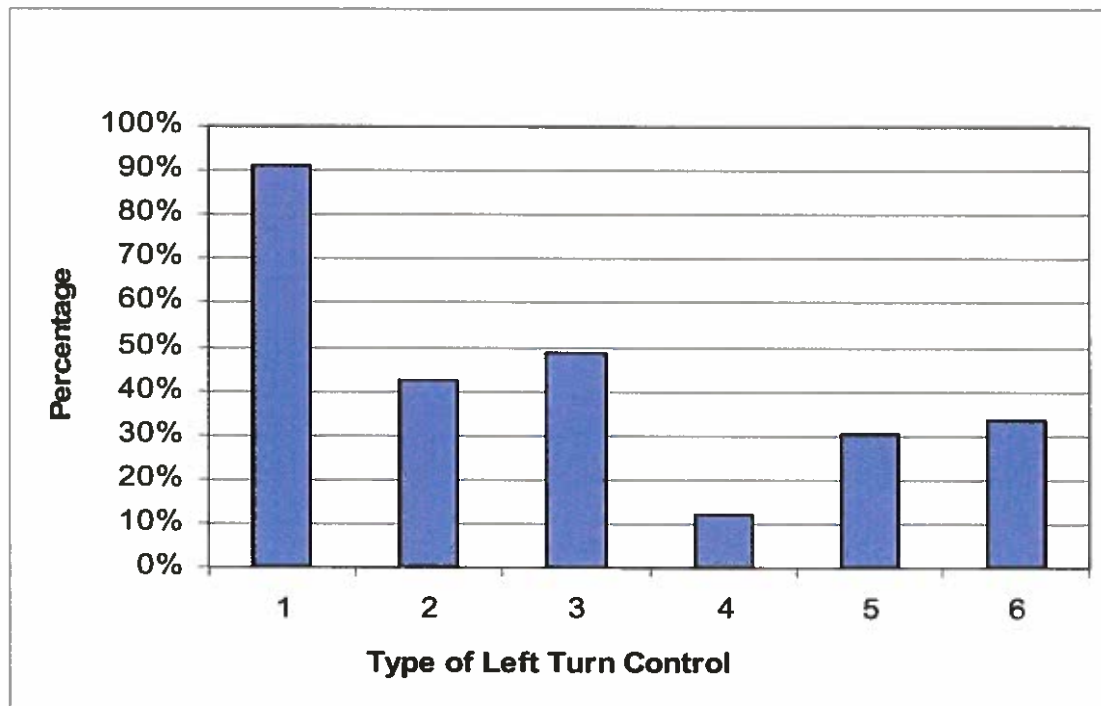


Figure 4 Survey Responses - Factor Ranking

The majority of the responses placed crash records at the top, followed by capacity/delay, size of intersection (e.g., number of lanes), and traffic progression. Cost was usually not a factor. The level of attention to citizen complaints varied among jurisdictions, but most agencies use complaints as a screening process for other potential problems. Other factors mentioned by several agencies include sight distance and other geometric factors (grade, speed, median), which are all closely related to crash and safety issues.

Types of Left-Turn Implementations

This question pertained to different types of left-turn operations implemented to achieve protected/permitted control. The objective of this question was to find out whether special operations have been implemented among jurisdictions beyond the MUTCD standard design for protected/permitted left-turn control. The summarized results are shown in Figure 5.



Note: The numbers indicate the types of left turn operations as:

- 1 Protected/Permitted (leading left turns only)
- 2 Permitted/Protected (lagging left turns only, non actuated)
- 3 Protected/Permitted lead/lag using standard MUTCD display
- 4 Protected/Permitted lead/lag using the Dallas Display (louvered display)
- 5 Protected/Permitted lead/lag using other display (please specify)
- 6 Other (e.g., detector setback to have permitted only operation, please specify)

Figure 5 Survey Responses on Left-turn Control Implementations

Protected/permitted with leading left-turns was the most common (91%), which is the recommended operation utilizing standard protected/permitted design to avoid the

yellow-trap condition. It was surprising to see that the second most popular left-turn operation (49%) was protected/permited with lead/lag using the standard MUTCD display, which involves the *yellow-trap* conditions. Protected/permited with lead/lag using the Dallas Display (louvered display) was not common (only 12%). Four agencies used detector setback (usually 2~3 cars from the stop line) to trigger left-turn phases. One agency used flashing-red-arrow for protected/permisive left-turn controls.

General Policy and Practice Regarding the Use of Lead-Lag Phasing

The question was related to the general policy and practice regarding the use of lead-lag phasing. About 61% of the agencies use lead/lag for the benefit of progression (e.g., bandwidth) and for the purpose of minimizing queue spillover. Only three responses expressed concerns on driver confusion by using lead/lag phasing. Alternating the sequence during different times of day does not seem to be a concern. Another case of using lead/lag is at tight diamond interchanges (i.e., signal spacing less than 400 ft). The issue on use of maximum recall for the lagging left-turn phase was raised to make sure the volume does not change significantly cycle by cycle.

Conditions When Protected/Permitted Left-Turn Control Is Not Allowed

The question was regarding the conditions under which protected/permited left-turn control is NOT allowed. The detailed responses are shown in Table 2.

Table 2 Conditions When Protected/Permitted Left-Turn Is Not Allowed

Conditions When Protected/Permitted Left-turn Control Is Not Used	Number of Responses	Frequency
1 Speed is greater than a threshold	9	33%
2 The number of through lanes is greater than a threshold	15	56%
3 The number of left-turn lanes is greater than a threshold	18	67%
4 The number of crashes is greater than a threshold	9	33%
5 Other	13	48%

Among the four conditions examined, the number of left-turn lanes was the most important consideration when protected/permitted left-turn should not be used. 12 out of the 18 responses in this category reported that protected/permitted left-turns should not be used when the number of left-turn lanes is greater than one. Six agencies will not allow protected/permitted control when the number of left-turn lanes exceeds two.

The number of through lanes was also a major concern, where 15 of the responses used this as a criterion. Nine reported three lanes as the threshold (i.e., do not use protected/permitted if the number of through lanes is greater than three), and the other six reported two lanes as the threshold.

Safety was also a significant concern. The condition under which protected/permitted left-turn control was not allowed varied from three crashes a year to six crashes a year from the survey responses.

Eleven responses indicated use of speed as a threshold when determining protected/permitted left-turn controls. Six agencies used 45 mph as the threshold, while five agencies used speeds higher than 45 mph. The highest speed was 55 mph by the Maryland State Highway Administration. Michigan DOT, who used 45 mph as a threshold, also indicated that speeds above 45 mph may still be allowed if site conditions justify. Among other considerations, sight distance was mentioned as an important factor.

Other Factors

This question asked about what other factors different agencies and organizations think important when determining left-turn control types that are not included in the current guidelines. Several factors were mentioned in the responses, including: pedestrian and bicycle volumes, feasibility of time-of-day operation (i.e., to operate at different modes of control during peak and off-peak), cycle length compatible to other signals in a system, and driver's expectation (treat main street and side street differently).

Preferences for Guidelines

This question aimed to seek agency opinions about what kind of guideline is preferred if new guidelines were to be developed. The question was described as “Would you favor simple-to-use (less detail) guidelines, or guidelines that involve and/or incorporate specific intersection-level information (crashes, number of turn lanes, speed, number of opposing through lanes, cross-products, etc.)?”

Responses to this question indicated that the majority agencies (16 out of 28) prefer specific guidelines that involve and/or incorporate specific intersection-level information, while the remainder preferred simple-to-use guidelines. Most agencies also indicated the importance of engineering judgment. When detailed guidelines are provided, explanations and reasoning behind each guideline should be given.

Survey Questions for Existing Flashing-Yellow-Arrow Implementations

Several questions were asked whether there were any issues involved with those agencies that have already implemented or are planning to implement the new Flashing-Yellow-Arrow display for protected/permissive left-turn control.

Eight agencies representing eight different states indicated that they either have implemented or are in the process of implementing the Flashing-Yellow-Arrow display. Among all the agencies who have implemented the Flashing-Yellow-Arrow display, the first implementation was around 2004. Based on limited data and experience, it seems the public understands the display well. No major complaints have been received for those agencies who have implemented the Flashing-Yellow-Arrow. Some agencies indicated that more implementations would likely to occur if the Flashing-Yellow-Arrow becomes a standard in the MUTCD.

3.2 Safety of Protected/permitted Left-turn Controls

This part of the literature review is related to the second research objective, addressing the safety aspects of the Las Vegas LT Display. The approach to achieving this objective was to conduct before-after studies based on the crash statistics.

The purpose of conducting before-after studies is to estimate the effectiveness of a treatment by comparing the crash statistics before and after the treatment. In this case, implementation of the Las Vegas LT Display can be considered as the treatment. Hauer (17) provides a systematic description of conducting before-after studies, including the following three major before-after study methods: 1) simple or naïve before-after study; 2) before-after study with comparison group; and 3) before-after study with Empirical Bayes (EB) method. The three methods have been widely accepted by researchers and engineers (18). Another useful factor named the *crash reduction factor* (CRF) can also be obtained from the before-after crash statistics (19, 20, 21). CRF is defined as the percentage of the original crashes that is prevented by the treatment. The following discussions provide an overview of the three before-after study methods documented in Hauer's book (17). Literature specifically related to safety and operation of protected/permitted left-turn controls is also provided.

Regardless of the methods to be used, there are two basic tasks for conducting a before-after study:

- Predict what would have been the crash frequency, π , in the “after” period had the treatment not been applied; and
- Estimate the actual crash frequency, λ , in the “after” period.

Estimation of the actual crash frequency, λ , in the “after” period is always performed using actual crash counts, i.e., $\lambda = L$, where L is the actual number of crashes. It is the different ways of predicting the crash frequency, π , that differentiates the three before-after study methods. A method is superior to the other when a better prediction of the after crash frequency can be achieved. As will be discussed next, the Empirical Bayes

method provides the best prediction of after-period crashes; however, it also requires a significant amount of data, which may not be readily available in most cases.

3.2.1 Simple or Naïve Before-After Study

The major assumption behind the simple before-after study is that nothing will change the safety performance except for the treatment, i.e., the number of “after” crashes will be the same as the “before” crashes had the treatment not been implemented. However, this assumption is unlikely to be true in most cases; therefore, the simple before-after study has significant limitations. Nevertheless, it is still commonly used in practice due to its simplicity and less data requirements. The four-step process as described by Hauer (17) for conducting a simple before-after study is outlined below:

- Estimate λ and predict π

$\lambda = L$, the actual crash count in the “after” period

$\pi = K$, the actual crash count in the “before” period

- Estimate the variance of π , $\text{VAR}(\pi)$

$\text{VAR}(\pi) = K$. This is based on the assumption that crashes follow a Poisson distribution where the variance equals to the mean.

- Estimate $\delta = \pi - \lambda$, where δ is a measure of safety improvement. A positive δ indicates an improvement on safety (i.e., reduction in crashes).

- Estimate the variance of δ , $\text{VAR}(\delta)$

$$\text{VAR}(\delta) = \text{VAR}(\lambda) + \text{VAR}(\pi)$$

Hauer (17) indicates a “useful rule of thumb” for making statistical conclusions based on the obtained statistics: if the actual crash frequency is within two standard deviations of the estimated crash frequency, reduction or increase of crash frequency is not statistically significant based on a 5% significance level ($\alpha = 0.05$). Otherwise, the

reduction or increase of crash frequency is statistically significant. For example, if $\pi - 2\sigma_\pi \leq L \leq \pi + 2\sigma_\pi$, where $\sigma_\pi = \text{sqrt}[\text{VAR}(\pi)]$ is the standard deviation of the estimated crash frequency in the “before” period, there will be no statistically significant difference between the crash frequencies during the “before” and the “after” periods.

3.2.2 Before-After Study with a Comparison Group

The before-after study with a comparison group method (also called the C-G method) improves its prediction of the after crash frequency by using comparison sites that have similar volume and geographic characteristics other than the treatment. Because it takes into account the other influencing factors, prediction of the crash frequency in the “after” period is more accurate compared to the simple before-after study method.

Major assumptions behind the C-G method include:

- The sundry factors that affect safety have changed from the “before” to the “after” period in the same manner on both the treatment and the comparison groups.
- The factors influence safety in the same way for both the treatment and the comparison groups.

The four-step process for conducting a before-after study using the C-G method is outlined below:

- Estimate λ and predict π

$\lambda = L$, the actual crash count in the “after” period for the treatment group;

$$r_T = r_C = (N/M)/(1+1/M) \approx N/M;$$

where

N = crash counts for the comparison group in the “after” period

M = crash counts for the comparison group in the “before” period

r_T, r_C = the ratios of “after” crash counts to “before” crash counts for the treatment group and the comparison group, respectively.

$\pi = r_T * K$; where K = the actual crash count in the “before” period for the treatment group

- Estimate $VAR(\pi)$

$$VAR(\pi) \approx \pi^2 [1/K + 1/M + 1/N + VAR(\omega)].$$

$$VAR(\omega) = s^2(O) - (1/K + 1/L + 1/M + 1/N).$$

Where $s^2(O)$ is the sample variance of the Odds Ratio, O , which is calculated by

$$O = (KN)/(LM)/(1+1/L+1/M)$$

- Estimate $\delta = \pi - \lambda$, where δ is a measure of safety improvement. A positive δ indicates an improvement on safety (i.e., reduction in crashes).
- Estimate the variance of δ , $VAR(\delta)$

$$VAR(\delta) = VAR(\lambda) + VAR(\pi)$$

Similarly, Hauer's (17) “useful rule of thumb” for making statistical conclusions can be used: if the actual crash frequency is within two standard deviations of the estimated crash frequency, reduction or increase of crash frequency is not statistically significant based on a 5% significance level ($\alpha = 0.05$). Otherwise, the reduction or increase of crash frequency is statistically significant. For example, if $\pi - 2\sigma_\pi \leq L \leq \pi + 2\sigma_\pi$, where $\sigma_\pi = \text{sqrt}[VAR(\pi)]$ is the standard deviation of the estimated crash frequency in the “before” period, there will be no statistically significant difference between the crash frequencies during the “before” and the “after” periods.

3.2.3 Before-After Study with Empirical Bayes (EB) Method

The Empirical Bayes (EB) method combines the strengths of regression and comparison group approaches, which can eliminate the “regression-to-mean” bias (21). The “regression-to-mean” phenomenon occurs when evaluating safety improvements at sites chosen based on higher-than-normal crash locations. In this case, the safety improvements are normally over estimated. To eliminate the “regression-to-mean” bias, the EB method estimates how many crashes would have occurred at the study site had no improvements been made by using the crash statistics from a group of similar comparison sites and from the study site prior to the treatment. This allows the engineer to compare the “after treatment” crash rate at the site to an estimate of the crash rate for the same site during the same time period had no treatment been done. Such a comparison mitigates the bias associated with “regression-to-mean” and time trends. Hauer (17) used the following equation to calculate the estimate of expected crashes at treatment sites.

$$E(k/K) = \alpha E(k) + (1 - \alpha)K \quad (1)$$

where

- $E(k/K)$ = estimate of the expected crashes at treatment sites,
- $E(k)$ = expected number of crashes at the reference sites,
- K = actual number of crashes at treatment site, and
- α = weight factor.

The weight factor is calculated as follows:

$$\alpha = \frac{1}{1 + \frac{VAR(k)}{E(k)}} \quad (2)$$

where $VAR(k)$ is the variance of the expected number of crashes at the reference sites. Thus, the expected number of after crashes had no improvement been made at the treatment sites is a function of how the ‘weight’ is assigned to the crashes expected at

the reference sites. If the 'weight' is chosen to be near 1, then the estimate of the expected crashes for treatment sites is close to the mean of its reference sites; if the 'weight' is chosen to be near 0, then the estimate of the expected crashes at the treatment sites will mainly reflect the recorded count of crashes (19)

The method for deriving the variables in Equation 9 is described by Hauer (17). Using his notation, k_1, k_2, k_3, \dots , are the number of crashes at reference sites 1, 2, 3, ..., respectively, whose characteristics were determined to be similar to those at the treatment sites. If $E(k)$ is the expected number of crashes at the reference sites and K is the actual crash count at the treatment sites, then $E(K/k)$ is the estimate of the expected number of crashes at the treatment sites given that the sites recorded K crashes.

The sample moments and multivariate regression method are two different methods for calculation of $E(k)$ and $VAR(k)$. The sample moment method requires large number of samples. The equations for the method of sample moments are:

$$E(k) = \bar{k} \quad (3)$$

$$VAR(k) = s^2 - \bar{k} \quad (4)$$

Where

\bar{k} = Sample mean of the crashes at the reference sites

s^2 = Variance of the crashes at the reference sites

The sample mean and variance of the crashes at the reference sites are calculated from following equations:

$$\bar{k} = \frac{\sum k N_k}{N} \quad (5)$$

$$s^2 = \frac{\sum (k - \bar{k})^2 N_k}{N} \quad (6)$$

Where

N = number of reference sites

N_k = number of treatment sites

The expected number of crashes and variance at the reference sites for the multivariate regression method are calculated for the following equations:

$$E(k) = \beta_0 \times \chi_1^{\beta_1} \times \chi_2^{\beta_2} \times \chi_3^{\beta_3} \times \dots \quad (7)$$

$$VAR(k) = \frac{[E(k)]^2}{b} \quad (8)$$

Where

β_0 = Constant

$\beta_1, \beta_2, \beta_3$ = Parameters of the independent variables

X_1, X_2, X_3, b = Gamma distribution parameters estimated from the crash data using the maximum likelihood method

3.2.4 Studies Related to Protected/Permitted Left-turn Safety

Other data analysis methods were identified in the literature that specifically pertained to studying protected/permitted left-turn controls (22). Some researchers (23, 24) used crashes per million left-turn vehicles to evaluate the relative safety of intersections and some others (25) evaluated total crashes using the odds ratio. Bonneson (26) developed the following equation to calculate the average crash rate in terms of left-turn crashes per million vehicles entering the intersection.

$$CR = \frac{4 \times 10^6 \times CL}{365 \times T \times A \times ADT} \quad (9)$$

where

CR = average crash rate,

- CL = number of left-turn crashes at study approaches,
- T = study period (in years),
- A = number of approaches studied, and
- ADT = average daily traffic volume.

The “4” in the equation represents four intersection approaches. It is included to normalize the computed crash rate to reflect a rate for a four-leg intersection with the same display on all approaches.

Bonneson and McCoy (26) evaluated five types of protected/permitted left-turn signal displays considering both safety and operational performance measures. Based on their study, the crash rate computed for each type of protected/permitted left-turn signal display ranged from 0.28 to 0.61 for the roadway average daily traffic (ADT) volumes of 5,600 to 30,500. The Washington Section of ITE (27) analyzed crash rates for several types of left-turn controls. This study included 89 sites and found that the crash rates ranged between 0.07 and 0.89.

A major study, NCHRP 3-54 (22) was conducted to evaluate various types of protected/permitted left-turn displays. In the study, crash rates of various protected/permitted left-turn displays (five section cluster, vertical and horizontal) were determined and compared. The study covered intersections in seven different states, and the crash rate ranged from 0.19 to 1.31, with an average rate of 0.51. Also during this study, the research team investigated how variability in local and intersection specific conditions affected the analysis results. The study identified a great deal of variability among the data even though it came from the same general area and represented the same signal display type. In addition to variation of local data, driver understanding of intersection controls and crash reporting practices may have been different from one area to another. The study also noted that differences in source data for traffic volumes could affect the crash rate. Some of the traffic volume data obtained by the participating agencies was limited to peak hour counts, which may have led to an overestimate or underestimate of the ADT.

4.0 DEVELOPMENT OF GUIDELINES FOR LEFT-TURN CONTROLS

According to the published literature related to left-turn control guidelines, a common characteristic of such guidelines is that certain factors usually dominate the decision making process. Thresholds were established for these factors which govern a control type. For example, most guidelines would recommend a protected-only left-turn control when any of the following conditions exist: (1) the speed is greater than 45 mph; (2) the number of left-turn lanes is greater than one; (3) the number of opposing through lanes is greater than two; (4) the left-turn volume is greater than 300 vph; or (5) the cross-product of left-turn and through traffic volumes is greater than 160,000 for a single opposing through lane. One of the major shortcomings of such guidelines is the lack of comprehensive consideration and weighting of all the factors when making the selection. While previous research efforts all recognized this issue and emphasized the importance of engineering judgments and weighting various factors, no guidelines have yet developed that provide a systematic approach to weighting factors while selecting left-turn signal control types.

Determining a left-turn signal control type involves consideration of many different factors, thus the decision is essentially a multiple attribute decision making process (28, 29, 30). Efforts were made in this research to develop guidelines that incorporate such a multiple attribute application. The following provides an overview of the guidelines developed in this research.

4.1 The New Left-turn Control Guidelines

Development of the new left-turn control guidelines was built upon consideration of all the factors included in the existing guidelines, but with the introduction of the multiple attribute decision-making principle. The research team initially produced a weighting-and-scoring scheme, and the scheme was modified and fine tuned based on panel feedback and field case studies. As will be shown later in the discussion, such a weighting-and-scoring scheme may need continued refinement to tailor to agencies'

needs and their specific policies. The computational engine is currently coded in a spreadsheet model.

Input Factors

The factors considered in the guidelines, which are required for the model input, include the following:

- Left-turn traffic volume, V_L , vph
- Opposing through traffic volume, V_T , vph
- Number of left-turn lanes, N_L
- Number of opposing through lanes, N_T
- Speed on the opposing approach, S , mph
- Sight distance for the left-turn traffic, L , ft
- Number of left-turn crashes, C_L , crash/year

In addition, whether the left-turn signal is on a coordinated system or not is also an input factor. This factor will be used to adjust the final score to favor a protected-only control over a protected/permitted control. The premise behind this factor adjustment is that protected-only control would allow usage of a lead-lag phasing to improve progression, while a standard MUTCD protected/permitted control cannot allow a lead-lag phasing due to the *yellow-trap* phenomenon discussed previously.

Factor Weighting

While the aforementioned factors all affect the selection of a left-turn control type, they may weigh differently on the decision making process, thus they should not be treated equally. The recommended weights of each factor are listed in Table 3. The sum of all

the weights should be equal to 1.0. Again, these weights were initially recommended by the research team and further refinement may be necessary.

Table 3 Recommended Factor Weights

Factor	Weight
Left-turn traffic volume	0.05
Cross product of left-turn and opposing through traffic volume	0.15
Number of left-turn lanes	0.10
Number of opposing through lanes	0.10
Speed on the opposing approach	0.10
Sight distance for the left-turn traffic	0.10
Number of left-turn crashes	0.20
Left-turn lane and opposing through lane combination ¹	0.20

Note: 1. This is an additional compounding factor, reflecting the added safety impact when combining the two factors of number of lanes.

Factor Scoring

Among the three left-turn control types (permitted, protected/permitted, and protected), each control type is assigned a numerical score for each input factor. The score is given based on a scale of 10. The score reflects the tendency of selecting a certain control type based solely on this factor. The sum of the scores for each factor should be equal to 10. Table 4 is a scoring example for the volume cross product factor.

Table 4 Scores for the Cross Product Factor (Single Lane)

Cross Product	Score		
	Permitted	Protected/Permitted	Protected
<=50,000	9.999	0	0
<=60,000	6	4	0
<=70,000	3	7	0
<=90,000	1	9	0
<=110,000	0	9	1
<=130,000	0	8	2
<=150,000	0	6	4
<=160,000	0	1	9
>160,000	0	0	9.999

As shown in Table 4, when the left-turn and through volume cross product is less than 50,000, permitted control has a score of 9.999 (almost 10), which means that, at this traffic volume level, a permitted left-turn control is most likely selected. Similarly, if the cross product is greater than 160,000, a protected control is most likely selected. This is exactly how the previous guidelines work. In order to eliminate such a single dominating effect, a high score of 9.999 is assigned instead of 10. A final decision will be based on a composite score, weighting all the influencing factors. However, such a model can be easily modified (by changing 9.9999 to 10) if agencies prefer determining a left-turn control type using absolute thresholds. *Appendix D* includes a complete scoring list for all the factors.

Guidelines Demonstration

Figure 6 illustrates the data flow and the computational process for the left-turn control guidelines using a generic intersection case.

The demonstration shown in Figure 6 indicates that protected-only control receives the highest index (51%) comparing with permitted (28%) and protected/permitted (21%). Therefore, protected-only control is most likely the best control type for this intersection. However, traffic engineering judgment may deem another control to be better for specified reasons, which should be documented.

Input Variables

Traffic Volume: Left-turn, vph	150
Traffic Volume: Opposing Through, vph	900
Number of Lanes: Left-turn	2
Number of Lanes: Opposing Through	2
Opposing Speed, mph	35
Sight Distance, ft	500
Number of LT Accidents, acc./yr	2
Coordinated (1 -Yes, 0 - No)	1

Sample Score (Only One Factor is Shown)

LT-Volume		PM	PP	PT
<=60	0	9.999	0	0
<=100	61	8	2	0
<=200	101	5	5	0
<=300	201	3	6	1
<=400	301	0	5	5
<=500	401	0	2	8
<=600	501	0	1	9
<=700	601	0	0	9.999
>700	701	0	0	9.999

Note: PM – Permitted; PP - Protected/permitted; PT – Protected.

Weighting and Scoring

		Weights	Raw Score			Weighted Score		
			PM	PP	PT	PM	PP	PT
Traffic Volume: Left-turn, vph	150	0.05	5.0	5.0	0.0	0.3	0.3	0.0
Cross Product	135000	0.15	6.0	4.0	0.0	0.9	0.6	0.0
Number of Lanes: Left-turn	2	0.1	0.0	3.0	7.0	0.0	0.3	0.7
Number of Lanes: Opposing Through	2	0.1	3.3	3.3	3.3	0.3	0.3	0.3
Opposing Speed, mph	35	0.1	3.3	3.3	3.3	0.3	0.3	0.3
Sight Distance, ft	500	0.1	3.3	3.3	3.3	0.3	0.3	0.3
Number of LT Accidents, acc./yr	2	0.2	3.3	3.3	3.3	0.7	0.7	0.7
LT&OppTH Lanes	22	0.2	0.0	0.0	9.999	0.0	0.0	2.0
Score (sum of weighted score * 8)						22.5	22.5	34.9
						28%	28%	44%

Results

	PM	PP	PT
Initial Score	22.5	22.5	34.9
Coordination Adjustment	22.5	16.8	40.7
LT Control Index	28%	21%	51%

Conclusion See Index of Each Control

Note: The coordination adjustment is between Protected/permitted and Protected. A 10% of the two total score is deducted from Protected/permitted and added to Protected)

Figure 6 A Demonstration of the Left-turn Guideline Spreadsheet

4.2 Application of the Guidelines – Case Studies

Three case studies based on intersections in Las Vegas, Reno, and Sparks were conducted to demonstrate the application of the guidelines and for validation of the guideline results. A total of 28 intersections were selected from three agencies in Nevada, including seven intersections from City of Sparks, nine intersections from City of Las Vegas, and twelve intersections from City of Reno. The reason for selecting these intersections was due to availability of peak hour traffic volume counts. Balancing the number of intersections from each jurisdiction was another factor when selecting these sites. In addition to the traffic volume counts, other necessary input factor data were also collected by on-site field surveys.

Based on the collected data, results of left-turn control types were obtained from the guidelines and are summarized in Table 5. The table includes intersection name, city, existing left-turn control type, and left-turn control indices from the guidelines. The results include both a.m. and p.m. peak periods. Based on the indices, a left-turn control type was recommended for each intersection.

The recommended left-turn control type (last two columns) was determined based on the following rules:

- If there was less than 5% difference between two control types, both control types were selected.
- The most restrictive control was used to determine the final control type. This rule applied to the two peak periods and the two approaches of a single roadway. For example, if the eastbound approach indicated a protected control, but the westbound approach indicated a protected/permitted control, a protected control was selected for both approaches. Similarly, if the p.m. peak indicates a protected control, but the a.m. peak indicates a protected/permitted control, a protected control was selected for the intersection.

Table 5 Case Study Results for the Left-turn Control Guidelines

Intersection	City	Existing Control		Time	Guideline Results (%)												Control Type	
		NB/ISB	EB/WB		NB			SB			EB			WB			NB/ISB	EB/WB
					PM	PP	PT	PM	PP	PT	PM	PP	PT	PM	PP	PT		
Sparks Blvd_Lincoln Way	Sparks	PT	PM	AM	44%	22%	34%	44%	22%	34%	47%	27%	27%	44%	29%	27%	PT or EB	PM
				PM	36%	30%	34%	26%	37%	47%	27%	27%	42%	29%	29%			
Sparks Blvd_Prater	Sparks	PT	PT	AM	36%	14%	50%	41%	25%	34%	34%	22%	44%	40%	31%	29%	PT	PT
				PM	18%	27%	54%	37%	29%	34%	21%	31%	48%	41%	28%			
Rock_Prater	Sparks	PP	PP	AM	44%	22%	34%	44%	22%	34%	44%	28%	28%	41%	31%	28%	PM	PM
				PM	41%	25%	34%	44%	22%	34%	41%	31%	28%	41%	31%	28%		
Rock_Glendale	Sparks	PT	PT	AM	26%	37%	37%	20%	28%	52%	36%	37%	28%	41%	31%	28%	PT	PT or PT
				PM	36%	30%	34%	24%	25%	51%	25%	31%	43%	35%	37%	28%		
Rock_Oddie Blvd.	Sparks	PP	PP	AM	40%	24%	35%	44%	22%	34%	44%	28%	28%	41%	31%	28%	PM	PM
				PM	40%	24%	35%	44%	22%	34%	43%	29%	28%	44%	28%	28%		
Pyramid_Prater.	Sparks	PP	PP	AM	44%	22%	34%	39%	26%	35%	44%	28%	28%	43%	29%	28%	PT or PP	PM
				PM	44%	22%	34%	23%	37%	41%	36%	37%	28%	43%	29%	28%		
Pyramid_Victorian	Sparks	NA	PP	AM	NA	NA	NA	NA	NA	NA	47%	27%	27%	44%	29%	27%	NA	PM
				PM	NA	NA	NA	NA	46%	28%	28%	44%	29%	27%				

To be continued

- *Notes: 1. PM-Permitted; PP-Protected/permitted; PT-Protected;
- 2. Shaded percentages were used to determine the control types;
- 3. The shaded cells for the control type indicate matching of existing control;
- 4. NA means that data was not available for that approach.

Washington_Rancho	Las Vegas	PTO	NA	AM PM	33%	19%	48%	32%	20%	48%	NA	PT	NA	
					15%	20%	65%	19%	32%	49%				
Washington_Lamb	Las Vegas	PP	NA	AM PM	32%	20%	48%	33%	19%	48%	NA	PT	NA	
					16%	31%	53%	22%	29%	49%				
Vegas_Buffalo	Las Vegas	PP	PP	AM PM	22%	29%	49%	25%	26%	49%	NA	PT	PM or PT	
					15%	21%	64%	22%	29%	49%				
Sahara_Cimarron	Las Vegas	NA	PP	AM PM	NA						NA	NA	PT	NA
					NA									
Cheyenne_Michael	Las Vegas	NA	PP	AM PM	NA						NA	NA	PT	NA
					NA									
Charleston_Maryland	Las Vegas	PP	PP	AM PM	25%	26%	49%	32%	20%	48%	NA	PT	PT	
					19%	31%	50%	19%	31%	50%				
Charleston_Main	Las Vegas	NA	PTO	AM PM	NA						NA	NA	PT	NA
					NA									
Charleston_Durango	Las Vegas	NA	PP	AM PM	NA						NA	NA	PT	PT
					NA									
Charleston_Cimarron	Las Vegas	NA	PP	AM PM	32%	20%	48%	25%	26%	49%	NA	NA	NA	PT
					15%	32%	53%	15%	32%	53%				
Charleston_Cimarron	Las Vegas	NA	PP	AM PM	32%	20%	48%	33%	19%	48%	NA	NA	NA	PT
					26%	25%	49%	32%	20%	48%				

Table 5 (continued)

- *Notes: 1. PM-Permitted; PP-Protected/permitted; PT-Protected;
 2. Shaded percentages were used to determine the control types;
 3. The shaded cells for the control type indicate matching of existing control;
 4. NA means that data was not available for that approach.

McCarran_Sierra Higlnds	Reno	PT	PM	AM	40%	22%	39%	40%	22%	39%	47%	27%	46%	28%	27%	PT	PM
				PM	22%	22%	56%	41%	21%	39%	46%	28%	44%	29%	27%		
McCarran_7th Street	Reno	PT	PP	AM	40%	22%	39%	40%	22%	39%	40%	31%	30%	43%	27%	PT	PP
				PM	27%	33%	41%	32%	28%	39%	40%	31%	29%	34%	40%		
McCarran_MaeAnne	Reno	PT	PT	AM	27%	33%	41%	33%	12%	55%	33%	27%	46%	28%	27%	PT	PT
				PM	21%	19%	60%	33%	12%	55%	32%	26%	44%	29%	27%		
McCarran_4th Street	Reno	PT	PT	AM	41%	21%	39%	40%	22%	39%	43%	26%	30%	30%	X	PM or PT	PT
				PM	41%	21%	39%	41%	21%	39%	27%	42%	30%	30%	X		
McCarran_Plumas	Reno	PP	PT	AM			X	18%	40%	42%	44%	22%	43%	23%	34%	PT	PM
				PM			X	20%	40%	40%	44%	22%	43%	23%	34%		
McCarran_Lakeside	Reno	PP	PT	AM	44%	29%	27%	27%	42%	30%	44%	22%	26%	35%	38%	PT	PT
				PM	33%	40%	27%	27%	29%	44%	44%	22%	34%	24%	52%		
Virginia_Neil	Reno	PT	PT	AM	34%	16%	50%	44%	22%	34%	34%	26%	40%	37%	40%	PT	PT
				PM	17%	14%	70%	43%	23%	34%	17%	26%	19%	40%	41%		
Virginia_Kietzke	Reno	PT	PT	AM	44%	22%	34%	44%	22%	34%	40%	29%	32%	22%	44%	PT	PT
				PM	31%	34%	35%	44%	22%	34%	36%	30%	34%	21%	46%		
S.Kietzke_S.Moana	Reno	PT	PT	AM	36%	14%	50%	34%	16%	50%	36%	21%	44%	21%	44%	PT	PT
				PM	28%	21%	51%	18%	16%	66%	20%	36%	44%	28%	44%		
Virginia_S.Moana	Reno	PT	PT	AM	36%	14%	50%	34%	16%	50%	43%	29%	28%	43%	28%	PT	PM
				PM	18%	26%	55%	18%	23%	58%	36%	37%	28%	36%	37%		
Virginia_Plumb	Reno	PT	PT	AM	32%	14%	54%	34%	16%	50%	27%	29%	44%	34%	22%	PT	PT
				PM	17%	27%	56%	18%	26%	55%	18%	32%	50%	23%	33%		
Kietzke_Plumb	Reno	PT	PT	AM	36%	14%	50%	34%	16%	50%	34%	22%	44%	34%	22%	PT	PT
				PM	27%	21%	51%	18%	28%	54%	24%	33%	44%	20%	36%		

Table 5 (continued)

- *Notes: 1. PM-Permitted; PP-Protected/permitted; PT-Protected;
 2. Shaded percentages were used to determine the control types;
 3. The shaded cells for the control type indicate matching of existing control;
 4. NA means that data was not available for that approach.

In Table 5, the yellow-shaded indices were used for determining the control types. The green-shaded control types indicate that they match the existing controls. Based on the results shown in Table 5, the following observations can be made:

- The recommended control types from the guidelines matched the best for the intersections in Reno. Among a total of 24 approaches from 12 intersections (both directions on one street), 19 directions matched the existing control types (about 80%). The majority of the recommended control types are protected control, which represents a more restrictive/conservative policy.
- The recommended control types from the guidelines matched the worst for the intersections in Las Vegas. Among a total of 18 approaches from nine intersections (both directions on one street), only two directions matched the existing control types (about 10%). While the majority of the recommended control types are protected control, the existing control types are primarily protected/permitted controls. The results clearly show the difference between Las Vegas and Reno in terms of left-turn control policies. Las Vegas has a tendency of using the less restrictive protected/permitted left-turn controls, representing a more aggressive policy.
- The recommended control types from the guidelines matched fairly well for the intersections in Sparks. Among a total of 14 approaches from seven intersections (both directions on one street), eight directions matched the existing control types (about 60%). The results reflect a policy that is between Reno and Las Vegas for selecting left-turn control types.
- Based on the case study results, it shows that the weighting-and-scoring scheme plays an important role in determining a left-turn control type. The scheme can be modified to tailor agencies' specific policies. However, it may seem difficult to derive a universal weighting-and-scoring scheme to satisfy all agencies' needs.

- Due to the nature of the multiple attribute approach, the new guidelines only produce control indices (composite scores) for each control type. These index values will guide the selection process. Consequently, engineering judgment still plays an important role in making the final decision.

4.3 Findings and Recommendations

The tasks related to development of the left-turn control guidelines resulted in the following major findings and recommendations.

Findings:

- The multiple attribute decision making approach seems to be promising for developing guidelines with a spreadsheet for selecting left-turn signal control types. It overcomes one of the major shortcomings of existing guidelines by making decisions based solely on an individual dominating factor. It allows the weighting of various factors and making a decision that aligns with typical engineering practices.
- The guidelines presented in this study are sensitive to the weighting-and-scoring scheme adopted in the model. The weighting-and-scoring scheme reflects engineers' preferences of one control over the other. It is also a representation of agency's specific policies while selecting left-turn control types, such as policies that emphasize safety over efficiency (more conservative) or vice versa. Such a difference in policies was clearly shown in the case study. Therefore, the weighting-and-scoring scheme will need to be modified to interests of the agencies.

Recommendations:

- It is recommended that Nevada agencies utilize the guidelines and spreadsheet based on a weighting-and-scoring scheme consistent with local policy. The spreadsheet guidelines should be continually refined based on field applications.

5.0 SAFETY DATA ANALYSES

5.1 Data Analysis Methodology

As discussed in Section 3.2, both the Empirical Bayes method and the before-after study with a comparison group method require data from comparison sites with similar volume and geographic characteristics other than the treatment. For this particular study, it is desired to compare whether the Las Vegas LT Display resulted in crash increases. Due to the fact that the majority of the study sites only operate the Las Vegas LT Display during certain time periods of a day, it would be prudent to compare the crashes that occurred only during the same time-of-day operation period. Such a specific situation makes it difficult to select a large number of comparison sites, because the study (treatment) sites all have different time periods of operation of the Las Vegas LT Display. The Empirical Bayes method does not seem to fit the need of this study, as the study sites do not necessarily represent high-crash locations to involve the “regression-to-mean” bias. As a result, a reasonable approach to selecting comparison sites is to use the cross street approaches at the same study intersections. In order to be considered as a comparison group, however, the cross-street approaches must have the standard protected-permitted left-turn display as specified in the MUTCD.

Due to the situations discussed above, this study adopted the following methods: (1) the simple before-after study method; (2) the before-after study method using the cross-street approaches of the same study intersections as comparison sites; and (3) the before-after study using crash rate based on Bonneson’s equation (26).

In typical traffic safety studies, a three-year analysis period is usually used to minimize the random variation of crash counts and the change of influencing factors over time. A two-year analysis period can also be used if data is not available for three years. In addition, the construction year (i.e., the year when the left-turn control modification occurred) should also be eliminated from the analysis period to minimize the effect of construction year.

5.2 Data Collection

There are currently ten intersections in the Las Vegas area operating with the Las Vegas LT Display. The Las Vegas LT Display operates on a time-of-day basis, mostly during the peak-hour periods. The intersection approach with the leading left-turn phase is normally the approach that uses the Las Vegas LT Display. The opposing (lagging) approaches continue to use the standard MUTCD protected/permitted display. The approaches using the Las Vegas LT Display may operate all day or may switch directions during different times of the day. The implementation dates of the Las Vegas LT Display vary, but most installations occurred around 1994-1995 and 2003-2004. Because crash data was only available through 2006 when the analysis was performed, a two-year analysis period (excluding the implementation year) was used for this study.

Table 6 includes information related to the ten sites. The table includes the approaches that use the Las Vegas LT Display, time of implementation, and the time periods of operation during the day.

**Table 6 Time of Day Operation of the Las Vegas Display
at the Study Intersections**

Intersection	Approach Using the Las Vegas Display	Year Implemented	Time of Day Operation Period
Dessert Inn & Arville	SB	2004	All day
Charleston & Lamb	SB	2003	Midday (11-13:00) and PM peak (16:00-18:00)
Spring Mtn. & Arville	NB	2004	All day
Upland & Jones	NB	2004	05:15-12:00 weekdays; 05:15-21:00 weekends
Nellis & Harris	NB	2004	Midday peak (11:00-13:00)
Charleston & Las Vegas	WB	1995	06:30-8:30, 11:30-19:00
	EB	1995	08:30-11:30, 19:00-22:00
Charleston & Main	WB	1995	06:30-11:30, 19:00-22:00
	EB	1995	06:30-08:30, 11:30-19:00
Buffalo & Oakey	SB	2003	PM peak (16:00-18:00)
Rancho & Washington	SB	1995	05:15-08:30, 19:00-22:00
	NB	1995	08:30-19:00
Decatur & Alta	SB	1994	05:15-06:30, 08:30-11:30, 19:00-22:00
	NB	1994	06:30-08:30, 11:30-19:00

Table 7 includes the intersection geometry and speed limits at the ten sites obtained during site visits in March 2006.

Table 7 Intersection Geometry and Speed with Las Vegas Display

Intersection	Approach	Street Name	# of Lanes	Speed
Desert Inn & Arville	NB	Arville	2 through, 1 left, 1 right	35
	SB*	Arville	2 through, 1 left	35
	EB	Desert Inn	2 through, 1 right	45
	WB	Desert Inn	2 through, 1 left, 1 right	45
Charleston & Lamb	NB	Lamb	3 through, 1 left	45
	SB*	Lamb	3 through, 1 left, 1 right	45
	EB	Charleston	3 through, 2 left	45
	WB	Charleston	3 through, 1 left	45
Spring Mtn. & Arville	NB*	Arville	2 through, 1 left, 1 right	35
	SB	Arville	2 through, 1 left	35
	EB	Spring Mtn	2 through, 1 left	45
	WB	Spring Mtn	2 through, 1 left	45
Upland & Jones	NB*	Jones	2 through, 1 left	35
	SB	Jones	2 through, 1 left, 1 right	35
	EB	Upland	1 through left shared, 1	25
	WB	Upland	1 through, 1 left, 1 right	25
Nellis & Harris	NB*	Nellis	3 through, 1 left	45
	SB	Nellis	3 through, 1 left	45
	EB	Harris	2 through, 1 left	25
	WB	Harris	2 through, 1 left	25
Charleston & Las Vegas Blvd	NB	Las Vegas	3 through, 1 left	30
	SB	Las Vegas	2 through, 1 left	30
	EB*	Charleston	3 through, 1 left	35
	WB*	Charleston	3 through, 1 left	35
Charleston & Main	NB	Main	2 through, 1 left	30
	SB	Main	2 through, 1 left	30
	EB*	Charleston	3 through, 1 left	35
	WB*	Charleston	3 through, 1 left	35
Buffalo & Oakey	NB	Buffalo	3 through, 1 left	35
	SB*	Buffalo	3 through, 1 left	35
	EB	Oakey	2 through, 1 left	35
	WB	Oakey	2 through, 1 left	35
Rancho & Washington	NB*	Rancho	2 through, 1 left, 1 right	35
	SB*	Rancho	3 through, 1 left	35
	EB	Washington	2 through, 1 left	35
	WB	Washington	2 through, 1 left	35
Decatur & Alta	SB	1994	05:15-06:30, 08:30-11:30,	
	NB	1994	06:30-08:30, 11:30-19:00	

Note: * Approach that uses the Las Vegas LT Display

Crash data at the study sites was obtained from NDOT for the two-year analysis periods before and after the Las Vegas LT Display was implemented. Table 8 includes information about intersection names, the approaches that use the Las Vegas LT Display, the analysis periods, crash counts, and the average crash per year.

It should be noted that the crash data in Table 8 only includes those crashes occurring during time periods in which the Las Vegas LT Display was in operation. Therefore, they only represent a portion of the crashes that occurred at the intersections. For the subject approach and the opposing approach, the crash data includes only left-turn related crashes. Crashes for the entire intersection, however, include all types of crashes. For example, at the Desert Inn & Arville intersection, the number of left-turn crashes during the after period for the subject approach is zero, and the total all-type crashes occurred during the after period at the same intersection is 26. Both numbers only include those crashes occurring during the time periods when the Las Vegas LT Display was in operation.

Table 8 Intersection Crash Data for the Subject and the Opposing Approaches Using Two-Year Before-After Analysis Periods

Intersection	Approach	Before Crash Period	After Crash Period	Number of Crashes ⁴	
				Before	After
Dessert Inn & Arville	Subject ¹ (SB)	2002-2003	2005-2006	5	0
	Opposing ² (NB)			1	2
	All ³			31	26
Charleston & Lamb	Subject (SB)	2001-2002	2004-2005	3	1
	Opposing (NB)			6	0
	All			10	1
Spring Mtn. & Arville	Subject (NB)	2002-2003	2005-2006	0	3
	Opposing (SB)			3	1
	All			12	12
Upland & Jones	Subject (NB)	2002-2003	2005-2006	0	0
	Opposing (SB)			3	7
	All			5	15
Nellis & Harris	Subject (NB)	2002-2003	2005-2006	3	1
	Opposing (SB)			0	0
	All			6	7
Charleston & Las Vegas ⁵	Subject (WB)	1993-1994	1996-1997	2	12
	Subject (EB)			0	1
	All			38	21
Charleston & Main	Subject (WB)	1993-1994	1996-1997	3	6
	Subject (EB)			3	7
	All			25	30
Buffalo & Oakley	Subject (SB)	2001-2002	2004-2005	0	1
	Opposing (NB)			0	0
	All			1	4
Rancho & Washington	Subject (SB)	1993-1994	1996-1997	1	0
	Subject (NB)			0	0
	All			18	1
Decatur & Alta	Subject (SB)	1992-1993	1995-1996	0	2
	Subject (NB)			1	3
	All			41	11
All Sites	Subject			21	37
	Opposing			13	10
	All			187	128

Note: 1. Subject Approach is the approach that runs the Las Vegas LT Display;

2. Opposing Approach is the approach opposite to the subject approach that runs standard protected/permitted display;

3. All includes all the approaches of an intersection;

4. The number of crashes is counted only during the periods when the Las Vegas LT Display was in operation;

5. The after crash counts for this intersection is unusually high, and is considered as an outlier.

By examining the overall changes of crash counts at all the study intersections, the number of left-turn crashes increased from 21 to 37 for the subject approaches that use the Las Vegas LT Display. The number of crashes decreased from 13 to 10 for the opposing approaches that use the standard MUTCD protected/permitted LT display. The number of all-type crashes decreased from 187 to 128 for the entire intersection. The number of crashes represents a very small sample size and significant variations can be observed among the sites. The intersection of Charleston & Las Vegas reveals an unusually large increase in crashes for the after period. The reason behind this large increase could not be immediately identified. However, if this intersection is included in the data analysis, it could cause a significant bias about the results. In general, if a sample is greater than three times the standard deviation from the mean, it is considered to be an outlier (31) and can be excluded from the sample. In this case, the mean was $37/14$ (subject approaches) = 2.6 so the standard deviation was 1.63 (assuming the crashes followed a Poisson distribution where the mean was equal to its variance). If a sample value is greater than 7.5, it is an outlier; therefore '12' is definitely an outlier and can be excluded from the sample. Further detailed statistical analyses are presented next based on the data presented in Table 8. The analyses only focused on the subject approaches.

5.3 Data Analyses

5.3.1 Simple Before-After Analysis

The results based on the simple before-after study method are presented next. The crash counts were based on all the study sites over a two-year-before and two-year-after analysis periods.

- Estimate λ and predict π

The estimated total crashes in the "after" period $\lambda = L = 24$

The predicted total crashes in the "after" period $\pi = K = 19$

- Estimate the variance and standard deviation of π , $\text{VAR}(\pi)$ and σ_π

$\text{VAR}(\pi) = K = 19$. $\sigma_\pi = \text{sqrt}(19) = 4.36$. This is based on the assumption that crashes follow a Poisson distribution, where the variance equals to the mean.

- Estimate $\delta = \pi - \lambda = 19 - 24 = -5$, an indication of increase of five crashes for all the study sties over a two-year period.
- At a 5% significance level ($\alpha = 0.05$), the confidence interval is estimated at $(\pi - 2\sigma_\pi, \pi + 2\sigma_\pi) = (10.28, 27.72)$.
- Since $10.28 < L < 27.72$, the crash increase was not statistically significant.

Although a conclusion was reached that the Las Vegas LT Display did not result in crash increases, the analysis was based on a rather small sample size. In order to increase the confidence level of the statistical results, further studies may be warranted within a few years.

5.3.2 Before-after Analysis with a Comparison Group

A before-after analysis with a comparison group was conducted for the study sites. Due to the special cases that the Las Vegas LT Display only operates during certain periods of a day, a large number of comparison sites could not be identified. Instead, the cross-street approaches of each study site that use standard MUTCD left-turn displays were selected as comparison sites, and the crashes during the same time periods when the Las Vegas LT Display was in operation were used for the analyses. Table 9 shows the crash data for the comparison sites (i.e., the cross-street approaches). Similarly, the crash data shown in Table 9 only includes left-turn related crashes and only during the periods when the subject approaches operated the Las Vegas LT Display. It can be seen from the table that there was a slight change (from 25 to 29) before and after the Las Vegas LT Display was implemented. It can also be noticed that the number of crashes is also very small for the comparison group.

Table 9 Crash Data for the Comparison Sites (Cross-street)

Study Intersection	Cross Street Approaches	Time Period of Operation	Before	After	Number of Crashes (2-Yrs)	
					Before	After
Dessert Inn & Arville	EB&WB	All Day	2002-2003	2005-2006	18	15
Charleston & Lamb	EB&WB	Midday (11-13:00) and PM peak (16:00-18:00)	2001-2002	2004-2005	2	0
Spring Mtn. & Arville	EB&WB	All Day	2002-2003	2005-2006	1	1
Upland & Jones	EB&WB	05:15-12:00 weekdays; 05:15-21:00 weekends	2002-2003	2005-2006	0	1
Nellis & Harris	EB&WB	Midday peak (11:00-13:00)	2002-2003	2005-2006	0	0
Charleston & Las Vegas	NB	06:30-8:30, 11:30-19:00	1993-1994	1996-1997		
	SB	08:30-11:30, 19:00-22:00			0	0
Charleston & Main	NB	06:30-11:30, 19:00-22:00	1993-1994	1996-1997	3	5
	SB	06:30-08:30, 11:30-19:00				
Buffalo & Oakey	EB&WB	PM peak (16:00-18:00)	2001-2002	2004-2005	0	1
Rancho & Washington	EB	05:15-08:30, 19:00-22:00	1993-1994	1996-1997	1	1
	WB	08:30-19:00				
Decatur & Alta	EB	05:15-06:30, 08:30-11:30, 19:00-22:00	1992-1993	1995-1996		
	WB	06:30-08:30, 11:30-19:00			0	5
All Sites					M=25	N=29

The analysis results are presented next.

- Estimate λ and predict π

The estimated crashes in the “after” period for the treatment group, $\lambda = L = 37$

$$r_T = r_C = (N/M)/(1+1/M) = (29/25)/(1+1/25) = 1.12$$

where N = crash counts for the comparison group in the “after” period

M = crash counts for the comparison group in the “before” period

r_T, r_C = the ratios of “after” crash counts to “before” crash counts, for the treatment group and the comparison group, respectively.

$$\pi = r_T * K = 1.12 * 21 = 23.5$$

- Estimate $VAR(\pi)$ and

$$VAR(\pi) \approx \pi^2 [1/K + 1/M + 1/N + VAR(\omega)].$$

$$VAR(\omega) = s^2(O) - (1/K + 1/L + 1/M + 1/N).$$

Where $s^2(O)$ is the sample variance of the Odds Ratio, O , which is calculated by

$O = (KN)/(LM)/(1+1/L+1/M)$ for each year, as shown in Table 10.

Table 10 Odds Ratio

Year	Study Approaches	Cross-Street	Odds Ratio, O
Before: Year 1	9	12	NA
Before: Year 2	16	9	0.37
After: Year 1	11	20	2.69
After: Year 2	18	17	0.47

From Table 10, the sample mean of the odds ratio was obtained at 1.18, and the sample variance, $s^2(O)$, was obtained at 1.72. According to Hauer (17), the sample mean of the odds ratio should be close to 1.0 in order for the analysis method to be valid. For the data shown in Table 10, the sample mean is close to 1.0; however, significant variations can be noticed for the individual years (e.g., an extremely high odds ratio at 2.69), which is probably due to the rather small sample size of the crash data.

$$VAR(\omega) = s^2(O) - (1/K + 1/L + 1/M + 1/N)$$

$$= 1.72 - (1/21 + 1/37 + 1/25 + 1/29) = 1.57.$$

$$\begin{aligned} \text{VAR}(\pi) &\approx \pi^2[1/K + 1/M + 1/N + \text{VAR}(\omega)] = 23.5^2[1/21+1/25+1/29+1.57] \\ &= 934.5. \end{aligned}$$

$$\sigma_\pi = \text{sqrt}[\text{VAR}(\pi)] = 30.6. \text{ This is a very high standard deviation, much higher than its mean.}$$

- Estimate $\delta = \pi - \lambda = 23.5 - 37 = -13.5$, an indication of increase of about 14 crashes for all the study sites over a two-year period.
- At 5% significance level ($\alpha = 0.05$), the confidence interval is estimated at $(\pi - 2\sigma_\pi, \pi + 2\sigma_\pi) = (-37.7, 84.7)$.
- Since $-37.7 < L < 84.7$, the crash increase was not statistically significant.

The results indicated a small increase of about 14 crashes for all the study sites due to implementation of the Las Vegas LT Display; however, the increase was not statistically significant according to the analysis results. It is noted that the analysis was also based on a very small sample size. In fact, the crash sample size was so small and the variation was so large that the lower threshold for significance was negative; it is impossible to have a negative number of crashes. Again, such a small sample size and high variation may warrant further investigations.

5.3.3 Analysis Based on Crash Rate

Due to the extremely small sample size shown previously, there is a potential risk of drawing invalid conclusions using the before-after study methods discussed above. Therefore, analyses based on left-turn crash rates were also conducted. The primary purpose of calculating left-turn crash rate was to compare with those found in the literature (22, 26, 27) that specifically focused on studying protected/permitted left-turn safety issues. Recall that the crash data presented earlier only included those during the time periods in a day when the Las Vegas LT Display was in operation. Also, each

intersection had different time periods and durations of operating the Las Vegas LT Display. In order to bring each crash frequency to a comparable level, a normalization process was performed. The normalization was to derive new crash frequencies that would be equivalent to the all-day crash measure, which can then be used to calculate the crash rates and to compare with those in the literature.

The normalization process is described in the following steps:

- All types of crashes during all day occurred at each intersection were determined for the before and after periods and are listed in column 5 and 6 in Table 11.
- The ratios of time-of-day crashes to all-day crashes were calculated using Equation (10), and are summarized in Table 11 as “Normalization Ratio”. This ratio was used to calculate the normalized crash frequency.

$$NR = \frac{N_{TOD}}{N_{ALL}} \quad (10)$$

where

- NR = normalization ratio,
- N_{TOD} = number of crashes during TOD,
- N_{All} = number of crashes all day,

- The normalized left-turn crash frequencies were obtained from Equation (11), and are shown in columns 9 and 10.

$$N_{Norm} = \frac{CF_{TOD}}{NR} \quad (11)$$

where

- N_{Norm} = normalized crash frequency (crashes per year),
- CF_{TOD} = crash frequency during TOD (crashes per year),
- NR = normalization ratio

Table 11 Normalized Crash Data

1. Intersection	2. Approach	# of Crashes ³ during TOD		# of all Crashes all day all approaches		Normalization Ratio		Normalized Crash Frequency (crash/year)	
		3. Before	4. After	5. Before	6. After	7. Before	8. After	9. Before	10. After
Dessert Inn &Arville	Subject ¹ (SB)	4	1			time of day operation is all day, ratio=1		2.0	0.5
	All ²	31	26	31	26			15.5	13.0
Charleston &Lamb	Subject (SB)	3	1			0.250	0.111	6.0	4.5
	All	10	1	40	9			20.0	4.5
Spring Mtn. &Arville	Subject (NB)	0	1			time of day operation is all day, ratio=1		0.0	0.5
	All	12	12	12	12			6.0	6.0
Upland &Jones	Subject (NB)	0	0			1.000	0.882	0.0	0.0
	All	5	15	5	17			2.5	8.5
Nellis &Harris	Subject (NB)	3	1			0.300	0.163	5.0	3.1
	All	6	7	20	43			10.0	21.5
Charleston &Las Vegas	Subject (WB)	3	12			0.950	1.000	1.6	6.0
	All	38	21	40	21			20.0	10.5
Charleston &Main	Subject (WB)	3	5			0.714	0.938	2.1	2.7
	All	25	30	35	32			17.5	16.0
Buffalo &Oakey	Subject (SB)	0	1			0.091	0.267	0.0	1.9
	All	1	4	11	15			5.5	7.5
Rancho &Washington	Subject (SB)	1	0			1.000	1.000	0.5	0.0
	All	18	1	18	1			9.0	0.5
Decatur &Alta	Subject (SB)	0	2			0.976	1.000	0.0	1.0
	All	41	11	42	11			21.0	5.5

Note: 1. Subject Approach is the approach that runs the Las Vegas Display;

2. All includes all-types crashes on all the approaches of the intersection;

3. The number of crashes is counted only during the periods when the Las Vegas LT Display was in operation.

The left-turn crash rate (crashes per million entering vehicles – C/MEV) was calculated for each study approach using Bonneson's equation (Equation (9)). The ADTs for the study approaches during the analysis periods were estimated based on the data published by NDOT. ADTs were available at only six of the ten study intersections, and the average of all available years was used to calculate the crash rates. The crash rates at the six intersections are shown in Table 12. An average crash rate of 0.45 C/MEV was obtained for both the before and the after periods.

Table 12 Left-turn Crash Rate at Six Study Intersections

Intersection	Before Period	After Period	Study Approach	Average Estimated ADT		Crash Rate C/MEV	
				Before	After	Before	After
Charleston & Lamb	2001-2002	2004-2005	NB, SB	75,631	82,649	0.83	0.17
Charleston & Las Vegas	1993-1994	1996-1997	WB, EB	58,986	60,072	0.60	0.87
Charleston & Main	1993-1994	1996-1997	WB, EB	51,232	51,880	0.91	1.27
Buffalo & Oakey	2001-2002	2004-2005	NB, SB	46,972	49,176	0.00	0.11
Rancho & Washington	1993-1994	1996-1997	NB, SB	47,549	52,596	0.23	0.00
Decatur & Alta	1992-1993	1995-1996	NB, SB	53,027	55,613	0.10	0.30
Average						0.45	0.45

Table 13 shows a comparison between this study and other studies found in the literature. It can be seen that the Las Vegas LT Display had the lowest average crash rate at 0.45 C/MEV.

Table 13 Crash Rates for Left Turns from Several Studies

Study	Crash Rate Range	Average Crash Rate, C/MEV
This Study (Las Vegas LT Display)	0.00-1.27	0.45
NCHRP 3-54 (MUTCD Standard Display)	0.19-1.31	0.51
Bonneson and McCoy (MUTCD Standard Display)	0.28-0.61	0.55

5.4 Findings and Conclusions

Based on the results from the analyses, the following findings and conclusions were reached regarding the safety aspects of the Las Vegas LT display:

Findings:

- The study intersections involved a small number of crashes before and after installation of the Las Vegas LT Display. One reason was that the Las Vegas LT Display only operated during a small portion of a day, typically the peak-periods. As a result, the number of crashes was very small. Based on this limited data, the various analyses did not reveal a significant increase in crashes when the Las Vegas LT Display was in operation.
- The traffic volume data were available only at six intersections where the left-turn crash rates could be calculated. These six intersections yielded an average of 0.45 crashes per million entering vehicles. This average crash rate was the lowest compared to the crash rates reported in previous studies in which the MUTCD standard left-turn displays were used.

Conclusions:

- Based on the results from various analysis methods, it can be concluded that the Las Vegas LT Display does not exhibit any obvious safety concerns when compared to the MUTCD standard protected/permitted left-turn display.
- To increase the sample size, it would require crash statistics be collected over a longer period of time. In addition, alternative evaluation tools maybe beneficial to truly evaluate the safety performance of the Las Vegas LT Display. For example, instead of totally relying on crash statistics which are highly random in nature, surveying of drivers' understanding of the Las Vegas LT Display or conducting field observations of drivers' behavior would provide additional useful information.

6.0 FINDINGS, CONCLUSIONS, AND RECOMMENTATIONS

This research project successfully achieved two major objectives related to the Las Vegas LT Display: (1) address the safety aspects of its use by conducting before-after crash analyses; and (2) develop guidelines for selecting left-turn control types using a multiple attribute decision making approach. Major findings, conclusions, and recommendations from this research are summarized below:

Left-turn Control Guidelines

Findings:

- The multiple attribute decision making approach seems to be promising in developing guidelines for selecting left-turn signal control types. It overcomes one of the major shortcomings of existing guidelines by weighting various factors and making a decision that aligns with typical engineering practices.
- The guidelines presented in this study are sensitive to the weighting-and-scoring scheme adopted in the model. The weighting-and-scoring scheme reflects engineers' preferences of one control over the other. It is also a representation of an agency's specific policies for selecting left-turn control types, such as policies that emphasize safety over efficiency (more conservative) or vice versa. Such a difference in policies was clearly shown in the case study. Therefore, the weighting-and-scoring scheme will need to be modified to tailor to engineers' and agencies' needs.

Recommendations:

- The guidelines should be further tested by the traffic engineers in Nevada's agencies for its validity of application. The model should be continually refined based on field applications.

Safety Aspects

Findings:

- The study intersections involved a small number of crashes before and after installation of the Las Vegas LT Display. One reason was that the Las Vegas LT Display only operated during a small portion of a day, typically the peak-periods. As a result, the number of crashes was very small. Based on this limited data, the various analyses did not reveal a significant increase in crashes when the Las Vegas LT Display was in operation.
- The traffic volume data were available only at six intersections where the left-turn crash rates could be calculated. These six intersections yielded an average of 0.45 crashes per million entering vehicles. This average crash rate was the lowest compared to the crash rates reported in previous studies in which the MUTCD standard left-turn displays were used.

Conclusions:

- Based on the results from various analysis methods, it can be concluded that the Las Vegas LT Display does not exhibit any obvious safety concerns when compared to the MUTCD standard protected/permitted left-turn display.
- To increase the sample size, it would require crash statistics be collected over a longer period of time. In addition, alternative evaluation tools maybe beneficial to truly evaluate the safety performance of the Las Vegas LT Display. For example, instead of totally relying on crash statistics which are highly random in nature, surveying of drivers' understanding of the Las Vegas LT Display or conducting field observations of drivers' behavior would provide additional useful information. In addition, at least 3 years of crash data may be collected and used for a before and after evaluation

7.0 IMPLEMENTATION ISSUES

This research project produced two major products. The first product is a documentation of the safety aspect of the Las Vegas LT Display based on before-after crash statistics studies. There are no direct field implementation needs associated with this outcome. The second major product is the development of new guidelines for selecting left-turn control types for the State of Nevada. The guidelines were developed using a multiple attribute decision making approach which weights the various factors used in selecting a left-turn control type. Thus, this multiple attribute based approach will not normally produce a definite choice of a certain left-turn control type, but rather a composite score similar to a fuzzy-logic approach. The weighting-and-scoring scheme used in calculating the composite score can be easily modified to tailor to agencies' specific policies.

The primary principles and application of the guidelines have been documented in this report. Implementation of the guidelines will simply involve distributing the spreadsheet model to the practicing engineers in the State of Nevada. The engineers will need to collect all necessary data for the required input variables. The spreadsheet model will produce a composite score (a control type index) for each type of left-turn control. Based on these composite scores along with engineering judgment and the overall agency policy, an appropriate left-turn control type can then be selected. The guidelines can be used for assessing the adequacy of existing left-turn controls, or for determining left-turn control types for future intersections. The guidelines should be continuously refined based on field experience and feedback from experienced traffic engineers.

APPENDICES

APPENDIX A: REFERENCES

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APPENDIX B: LOGIC OF THE LAS VEGAS LEFT TURN DISPLAY

To implement the special left-turn control and operation, it requires modifications of the controller logic and relay wiring. For example, the logic enables programming in a controller to lag any left turn or a combination of turns as well as the ability to run any of the 5-section heads in a protected mode. This can be done in any plan table or in the schedule table by time of day. There might be different ways of implementing the logic. The procedure described here is based on what has been done in Las Vegas, and Mr. David Crisler from FAST Traffic Management Center in Las Vegas contributed the written documentation of the logic.

Wiring:

The 5-section heads are wired with the red ball/arrow, yellow arrow, and the green arrow tied to the turn phase loadswitch (1, 3, 5, and 7). The yellow and green balls for these heads are wired to loadswitch 9, 10, 11, and 12.

Conflict Monitor Relay:

This relay is necessary to satisfy the Conflict Monitor's lack of output circuitry. When a turn phase loadswitch is driven dark (during the permissive turn), this relay becomes energized to apply voltage to the red input of the conflict monitor. At all other times, the monitor is 'watching' the displayed lamp in the field. The relay drive logic checks for the lack of red, yellow, and green drives on the protected turn phase load switch (1,3,5 or 7). This logic uses the unused ped clear outputs to drive the relays as noted below. This also allows each conflict monitor channel to run with both red enable and the plus enable (Guardian) or Dual indication monitoring (EDI) as exactly one Red, Yellow, or Green, phase output is driven at all times. Relay wiring for this display is shown in Figure B-1.

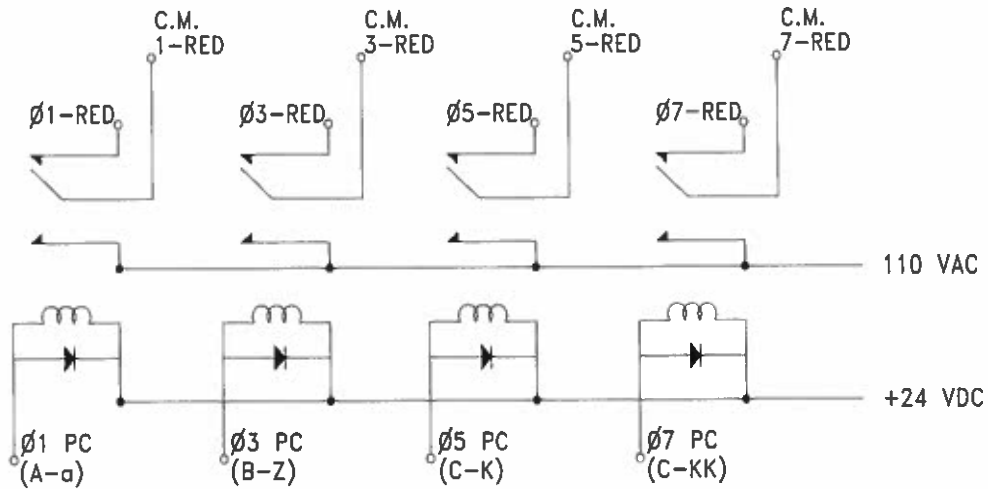


Figure B-2 Relay Wiring for the Display

Phasing and Ring Structure:

Ring 1	1,2,a,3,4,b
Ring 2	5,6,a,7,8,b
Ring 3	12,11,a,14,13,b
Ring 4	16,15,a,18,17,b

The first two rings are standard dual ring 8 phase, the third and fourth rings are made up of phases 11, 13, 15, and 17 to run the permissive turn balls. Phases 12, 14, 16, and 18 are required to give the controller a place to rest when not in the turn phases. A minimum recall in phases 11, 13, 15, and 17 will call the permissive turn unless it is omitted by the lack of a concurrent phase green or the presence of an AUX program bit. (Ex: 4G OR AUX 7 → OMIT 17.) Clearance timing in phases 11, 13, 15, and 17 are the same as the concurrent through phases.

Operation:

The red drives on the turn phase load switches (1, 3, 5, and 7) are determined by the lack of any other display on that head. (Ex: phase 4 Green + phase 4 Yellow + phase 17 Green + phase 17 Yellow → phase 7 Red.)

This changes the display so that the red indication is not on with any other lamp in that particular head. (No more 'red ball over a green arrow'.) This also means that the red indication can be safely (and properly) changed from a ball to an arrow, making it clear that this head is for turning traffic only. The 5-section balls are never displayed without the concurrent Green or Yellow balls (respectively) due to the ring structure, so louvers or other visually limiting devices are not necessary.

The sequence priority table determines the phase sequence, just as with protected heads, however, to avoid the yellow trap, an AUX bit must be set to protect the opposing turn.

Example: To lag phase 1, use sequence table 2 (reverse phases 3 and 4) in the controller and set AUX bit 7 (protect phase 7).

The sequence table is chosen in the plan table, and the AUX bit can be set in the plan table or in the schedule table. The AUX bit offers another option, a turn can be protected by time of day for reasons other than avoidance of the yellow trap. For example, if the 5-section operation is causing a safety concern during a particular time of day, it can be protected during that time without regard to the sequencing.

If changing the sequence while running on the street, set the AUX bit first, once the desired turn runs protected then set the sequence. If the sequence change is programmed without the AUX bit, the lagging protective turn will be omitted.

APPENDIX C: AGENCY SURVEY

Original Survey Form and Questions

Evaluation of Safety and Efficiency of Protected/permmissive Left-turn Controls

This survey is part of a research project sponsored by the Nevada Department of Transportation, to evaluate the safety and efficiency of a special type of left-turn control at signalized intersections, currently being used in the Las Vegas area. The special left-turn control uses standard protected/permmissive left-turn design, but operates with protected-only (green arrow with blackouts of the green ball and the yellow ball) and protected/permmissive, depending on time-of-day traffic conditions. This research also aims at developing guidelines for determining appropriate left-turn controls. Your input is greatly appreciated!

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Reno, NV 89557
zongt@unr.edu
Tel: 775-784-1232*

1. Personal Information

Name:

Organization:

Email:

Telephone:

2. What specific guidelines, if any, does your jurisdiction follow when determining left-turn control types (Please specify the document name(s), sources, and brief description of the applications, including in-house prepared documents).

permmissive vs. protected only

permmissive vs. protected/permmissive

protected only vs. protected/permmissive

3. Rank the factors and fill in the number (1 indicates the most important) when determining the type of left-turn controls. Put " * " if the item is not really considered.

Crash Records	<input type="text"/>
Traffic Progression	<input type="text"/>
Capacity and Delay	<input type="text"/>
Costs	<input type="text"/>
Citizen Complains	<input type="text"/>
Size of Intersection (such as number of lanes)	<input type="text"/>
Travel Speed	<input type="text"/>
Other (please specify)	<input type="text"/>

4. Has your agency implemented any of the following operations? Please check the item(s).

- Protected/Permitted (leading left turns only)
- Permitted/Protected (lagging left turns only, non actuated)
- Protected/Permitted lead/lag using standard MUTCD display
- Protected/Permitted lead/lag using the Dallas Display (louvered display)
- Protected/Permitted lead/lag using other display (please specify)

- Other (e.g., detector setback to have permitted only operation, please specify)

5. What is the general policy and practice regarding the use of *lead-lag phasing* in your jurisdiction?

- Does not use *lead-lag* phasing due to concern of driver confusion
- The sequence must be consistent all the time if *lead-lag* is used
- Use *lead/lag* for the benefit of progression (e.g., bandwidth)
- Use *lead/lag* for the purpose of minimizing queue spillover
- Other (specify)

6. Select from the following conditions when protected/permitted left-turn control is NOT allowed

- Speed is greater than a threshold (e.g., 40 mph) (specify the speed)
- The number of through lanes is greater than a threshold (e.g., more than 2 lanes) (specify the number of lanes)
- The number of left-turn lanes is greater than a threshold (e.g., more than 1 lane) (specify the number of lanes)
- The number of crashes is greater than a threshold? (specify the number of crashes)
- Other (specify)

7. What other factors do you think important while determining left-turn control types that are not being included in the current guidelines?

8. Would you favor simple-to-use (less detail) guidelines, or guidelines that involve and/or incorporate specific intersection-level information (crashes, number of turn lanes, speed, number of opposing through lanes, cross-products, etc.)?

* Please complete the following questions 9~15 **ONLY IF** you have implemented or are planning to implement the new *Flashing-Yellow-Arrow* (FYA) display for protected/permissive left-turn controls.

9.

Time of first implementation (month/year):

How many intersections:

Total number of intersection approaches:

Cabinet Type:

Controller Make and Model:

Conflict Monitor Make and Model:

Do you use special external logic:

Do you use special external hardware (relay, etc.):

Do you use protected-permitted lead-lag operation at any intersections with FYA?

10. What happens when there is an emergency pre-empt?

11. What does the local first response agencies think of this operation?

12. What, if any, public reactions have you received?

13. What, if any, public outreach has your agency provided?

14. Do you plan to install more of the FYA operation? If not, why?

15. Based on your observation or based on actual crash reports, what has happened to the crash frequency and type of crashes?

16. Other comments:

Survey Responses

Q1: What specific guidelines, if any, does your jurisdiction follow when determining left-turn control types (Please specify the document name(s), sources, and brief description of the applications, including in-house prepared documents).

Table C-1 Survey Responses on Types of Guidelines for Left Turn Controls

Organization	Permissive vs. Protected only	Permitted vs. Protected/Permissive	Protected only vs. Protected/Permissive
Arizona DOT	Arizona DOT Policies, Guidelines & Procedures PGP-4C-3-3	Arizona DOT Policies, Guidelines & Procedures PGP-4C-3-3	Arizona DOT Policies, Guidelines & Procedures PGP-4C-3-3
Oregon DOT	Oregon DOT signal policy and guidelines	Oregon DOT signal policy and guidelines	Oregon DOT signal policy and guidelines
Utah DOT	UDOT 06C-52: Left-Turn Phases at Signalized Intersections Revised January 5, 2006.	This is addressed in the policy listed above. The policy above has 4 warrant criteria when to select permissive/protected phasing.	This is based on engineering judgment that takes into account the number of opposing lanes to cross, the approach speed, crash rates, geometries, site distance, etc.
King County Department of Transportation	ITE & King County Department of Transportation guidelines	ITE & King County Department of Transportation guidelines	ITE & King County Department of Transportation guidelines
New Jersey DOT	MUTCD guidelines	MUTCD guidelines	MUTCD guidelines
City of Toronto Transportation Services	In-house	In-house	In house
Metro (Nashville) Public Works	Selection Criteria for Left-Turn Phasing from Traffic Engineering Handbook pages 475-76 (originally TRR 1421)	Selection Criteria for Left-Turn Phasing from Traffic Engineering Handbook pages 475-76 (originally TRR 1421)	Selection Criteria for Left-Turn Phasing from Traffic Engineering Handbook pages 475-76 (originally TRR 1421)
Missouri DOT	Capacity and safety warrants developed by MODOT	Capacity and safety warrants developed by MODOT	Capacity and safety warrants developed by MODOT
Washington State DOT	Cross Product => 50,000 for left turn phasing, WSDOT Northwest Region guidelines for left turn treatment and engineering judgment	Cross Product => 50,000 for left turn phasing, WSDOT Northwest Region guidelines for left turn treatment and engineering judgment	Cross Product => 50,000 for left turn phasing, WSDOT Northwest Region guidelines for left turn treatment and engineering judgment
Michigan DOT	Delays and crashes	Delays and crashes	Dual left turn lanes, sight distance, crashes, speed, lane usage
SRF Consulting Group	Depends on speeds	Protected/permissive used for intersections without separate turn lanes and only one left turn is heavy	Protected only is used with speeds 45 mph and above, double left turn lanes, or with wide medians where the left turns do not have good sight distance. It is also used if a variable sequence is being used
City of Kennewick, Washington	Engineering judgment (look at a variety of factors)	Engineering judgment - typical considerations include delay and crashes (delay normally is a greater issue)	Engineering judgment - normally volume and crashes with crashes
City of Tucson, Arizona	Infrequently used	Unclogging Arterial , PTI, FHWA FHWA-OP-03-069	Nearly signals are p/p lagging

Louisiana Department of Transportation and Development	LOS, Delays, accidents	EDSM Manual for left turn phasing	Traffic volumes, progression issues
City of Wilmington, North Carolina	LT, Thru volumes, sight distance, gap availability, LT delay	LT, Thru volumes, sight distance, gap availability, LT delay, variation of LT volume by TOD	LT, Thru volumes, sight distance, gap availability, LT delay, variation of LT volume by TOD
Charlotte Department of Transportation	Permissive as standard, protected only based on safety/crashes.	Permissive as standard, protected/permissive based on volume and delay criteria.	Protected/permissive based on volume and delay criteria. Protected only based on safety/crashes.
Harris County Public Infrastructure Department	Permissive only on minor cross streets	Protected/permissive at "T" intersections with good sight distance	Protected only for arterial streets with opposing left-turns
City of Little Rock, Arkansas	Permissive when the product of the left turn times the opposing traffic is less than 50,000 for single lane approach, 100,000 for 2 lane opposing	Permissive when the product of the left turn times the opposing traffic is less than 50,000 for single lane approach, 100,000 for 2 lane opposing	Protected only with multiple left turn lanes or sight distance problems and when opposing traffic is too great to provide adequate gaps
Kimley-Horn Associates, Inc.	Sight distance	Cross product rule	Cross product, sight distance
City of Arlington, Texas	Speed, sight dist, #crossing lanes, accidents	Speed, sight dist, #crossing lanes, accidents	Speed, sight dist, #crossing lanes, accidents
Retired traffic Engineer - 35 + years	Three or more lanes crossed - protected only	See above + volume of turning traffic	Same as above
Seattle Dept. Of Transportation	Volume with no LT to permissive vs. in-house crash record, Volume with no LT to permissive vs. # of turn lanes		In-house crash record vs. # of turn lanes
City of Rancho Cucamonga, California	We rarely install permissive only	We rarely install permissive only	Protected only with more than two approaching lanes, P/PLT elsewhere
Douglas County			Accidents or # lanes
City of Glendale, Arizona			Dual lefts are protected only, otherwise protected done on a case by case basis
City of Boulder, Colorado		Time of day using ITE guidelines, primarily excess accidents or delay.	Time of day due to excess accidents, or high volume/high speed.
Maryland State Highway Administration		Modified version of the Upchurch guideline developed from an Arizona study some years back	
City of Milwaukee, DPW, Wisconsin	City Standard practices - no written documentation	City Standard practices - no written documentation	City Standard practices - no written documentation
Iteris	None	None	None

Q2: Rank the factors and fill in the number (1 indicates the most important) when determining the type of left-turn controls. Put " * " if the item is not really considered.

Table C-2 Survey Responses on Important Factors for Determining Type of Left-Turn Controls

Organization	Factors Considered*							
	1	2	3	4	5	6	7	8
Arizona DOT	3	x	x	x	x	1	2	Traffic Volume - 4
Caltrans	1	6	2	7	5	4	3	
Campbell, California, California	3		1			2	4	
Charlotte Department of Transportation	1	4	2	x	x	x	3	
City of Milwaukee, DPW	2	x	1	Typically not a factor	Only to screen for potential new locations	3 (only with respect to a multiple lane configuration)	Typically not a factor	Geometric Factors; Approach grade and visibility of opposing traffic
City of Arlington, Texas	1	5	4		1+2+3+4+5 = Citizen complaints	2	3	Each is evaluated on its own merits
City of Boulder, Colorado	1	5	2	* Where adding left-turn heads requires a signal pole replacement, cost may determine how soon the change can be made.	x	3	4	Protected-only phasing to be used w/ triple left-turn.
City of Glendale, Arizona	2	4	1		3			
City of Kennewick, Washington	1	3	1	5	4*	6	7	
City of Little Rock, Arkansas	1	2	5	7	3	4	6	
City of Rancho Cucamonga, California	2	x	x	x	x	1	x	We almost always install left turn phasing for roadways with at least a left turn lane, almost never if only one approach lane.

City of Toronto Transportation Services	1	5	4	x	* only prompts engineering review	3	2	
City of Tucson, Arizona	4 Total crashes not just LT	2	3	7	8	5	6	1 left turn sight distance
City of Wilmington, North California	1	5	2	x	x	3	4	Left turn sight distance
Douglas County	1	3	x	x	x	2	x	
Harris County Public Infrastructure Department	3	4	5	7	6	1	2	
Ileris	*, unless a problem is obvious, in which case this becomes the highest priority	2	3	x	6	4	5	Left-turner sight distance of opposing traffic--1
Kimley-Horn	1	6	4	5	7	3	2	
Kentucky Transportation Cabinet	2	6	3	x	5	4 (tie)	4 (tie)	1 Volumes (namely cross-products)
Louisiana Department of Transportation and Development	1	3	2	x	4	x	5	Geometry, sight distance
Louisiana DOTD	2	4	1	x	6	3	5	
Maryland State Highway Administration	1		2	x	x	3	4	
Metro (Nashville) Public Works	2	4	1	x	3	5	6	Left turn trap (always protected-only if opposed by a lagging left turn)
Michigan DOT	2	5	1	x	6	4	3	
Missouri DOT	1	1	1	2	2	1	1	
New Jersey DOT	1	x	2	x	3	x	x	
Oregon DOT ¹	1	2	2	2	2	1	1	
Oregon DOT ²	1	3	2	5	5	1	1	2 volume of through and opposing
PB	1	4	3	5	2	6	7	
Retired traffic Engineer - 35 + years	2	3	4	5	7	1	6	
Seattle Dept. Of	1	5	2	4	6	3	x	

Transportation								
SRF Consulting Group	1 if speed, width and no. Of lanes not already met	4 (1) if variable phase order is used	5	6	7	2 (double left turn lanes)	1	3 median width
Utah DOT	1	6	5	8	7	3	2	4) site distance; geometrics
Washington State DOT	1	6	5	7	4	2	3	

* Note: The numbers indicate the type of factors as:

- 1 Crash Records
- 2 Traffic Progression
- 3 Capacity and Delay
- 4 Costs
- 5 Citizen Complains
- 6 Size of Intersection (such as number of lanes)
- 7 Travel Speed
- 8 Other (please specify)

* Two responses were received from Oregon DOT. Oregon DOT¹ and Oregon DOT² were used to differentiate.

Q3: Has your agency implemented any of the following operations? Please check the item(s).

Table C-3 Survey Responses on Different Left Turn Control Implementations

Organization	1*	2	3	4	5	Specify 5	6	Specify 6
Arizona DOT	Yes	Yes	Yes	No	No		No	
Caltrans	No	No	No	No	No		Yes	Protected only
Campbell, California	Yes	Yes	No	No	No		No	
Charlotte Department of Transportation	Yes	No	No	No	Yes	Flashing yellow arrow	No	
City of Milwaukee, DPW, Wisconsin	Yes	Yes	Yes	No	No		Yes	Detection is typically by third vehicle loops
City of Arlington, Texas	Yes	No	No	Yes	No		No	
City of Boulder, Colorado,	Yes	No	No	No	Yes	Flashing Yellow Arrow display	No	
City of Glendale, Arizona	Yes	Yes	No	No	No		Yes	We use 3rd car detection at nearly all signals with protected permitted heads
City of Kennewick, Washington	Yes	No	No	No	Yes	Flashing yellow arrow (FYA)	Yes	2 - 3 vehicle setback for left-turn detection, P/P and/or protected only operation by time-or-day/conditions
City of Little Rock, Arkansas	Yes	No	No	Yes	No		No	
City of Rancho Cucamonga, California	Yes	No	No	No	No		No	
City of Toronto Transportation Services	Yes	No	No	No	No		No	
City of Tucson, Arizona	Yes	Yes	Yes	Yes	No	Most signals are lagging P/P	Yes	Double activate left turn as lead then if still needed then lag
City of Wilmington, North California	Yes	No	No	No	Yes	Flashing yellow arrow, and P/P on the lagged side with Prot Only on the lead side	No	
Douglas County, State?	Yes	No	No	No	Yes	Lead/lag only with protected	Yes	Time of day PO vs. P/P operation at 2 intersections
Harris County Public Infrastructure Department	No	No	Yes	No	No		Yes	We only allow 5-Section left-turns at "T" intersections or diamond interchanges
Ileris	Yes	Yes	Yes	No	No		No	
Kimley-Horn	Yes	No	No	No	No		No	
Kentucky Transportation Cabinet	Yes	No	No	No	No		No	
Louisiana Department of Transportation and Development	Yes	No	Yes	No	No		No	
Louisiana DOTD	Yes	Yes	Yes	No	No		No	
Maryland State	Yes	Yes	Yes	No	No		Yes	Flashing Red arrow

Highway Administration								
Metro (Nashville) Public Works	Yes	Yes	Yes	No	No		No	
Michigan DOT	Yes	Yes	Yes	No	No		No	
Missouri DOT	Yes	Yes	Yes	Yes	No		Yes	Protected/permissive by time of day
New Jersey DOT	Yes	No	Yes	No	No		No	
Oregon DOT	Yes	No	No	No	Yes	4 section head w/ flashing yellow arrow experimental MUTCD	No	
PB	Yes	Yes	Yes	No	Yes		No	
Retired traffic Engineer - 35 + years	Yes	No	Yes	No	Yes	Older locations still have problems with yellow trap	Yes	Not sure what this means
Seattle Dept. Of Transportation	Yes	Yes	Yes	No	No		No	
SRF Consulting Group	Yes	No	Yes	No	No		Yes	Detector setback calling and also permitted protected lagging, but definitely actuated with detector cross switching with through phase
Utah DOT	Yes	Yes	No	No	Yes	One of our cities who controls some of our intersections has used the lag lefts on permitted/protected phasing. They love it, we hate it.	No	
Washington State DOT	No	No	No	No	Yes	We try to stick with the 5 section "doghouse" display	No	
<p>* Note: The numbers indicate the types of left turn operations as:</p> <p>1 Protected/Permitted (leading left turns only)</p> <p>2 Permitted/Protected (lagging left turns only, non actuated)</p> <p>3 Protected/Permitted lead/lag using standard MUTCD display</p> <p>4 Protected/Permitted lead/lag using the Dallas Display (louvered display)</p> <p>5 Protected/Permitted lead/lag using other display (please specify)</p> <p>6 Other (e.g., detector setback to have permitted only operation, please specify)</p>								

Q4: What is the general policy and practice regarding the use of lead-lag phasing in your jurisdiction?

Table C-4 Survey Responses on General Policy and Practice Regarding the Use of Lead-Lag Phasing

Organization	1*	2	3	4	5
Arizona DOT	No	Yes	No	No	
Caltrans	No	No	No	No	
Campbell, California, California	No	No	Yes	Yes	
Charlotte Department of Transportation	No	Yes	No	No	
City of Milwaukee, DPW, Wisconsin	No	Yes	Yes	No	
City of Arlington, Texas	No	No	Yes	Yes	Use Dallas phasing when the benefit is large and provable.

City of Boulder, Colorado	No	No	Yes	No	
City of Glendale, Arizona	No	No	No	No	We use leading and lagging phasing at different intersections. We will begin using lead-lag phasing to promote progression. We hope to alter this by time of day as needed but this has not been determined yet.
City of Kennewick, Washington	No	No	Yes	Yes	
City of Little Rock, Arkansas	No	No	Yes	Yes	
City of Rancho Cucamonga, California	No	No	Yes	Yes	
City of Toronto Transportation Services	Yes	No	No	No	
City of Tucson, Arizona	No	No	No	Yes	
City of Wilmington, North Carolina	No	No	Yes	Yes	Default to lead-lead if no coordination benefit
Douglas County	No	No	Yes	No	
Harris County Public Infrastructure Department	No	No	Yes	Yes	
Iteris	No	No	Yes	Yes	No problem with varying sequence by time of day.
Kimley-Horn	No	No	No	No	Protected only lefts may be lagged by time of day but differs by municipality
Kentucky Transportation Cabinet	No	No	Yes	Yes	
Louisiana Department of Transportation and Development	No	No	Yes	No	
Louisiana DOTD	No	Yes	No	No	
Maryland State Highway Administration	No	No	Yes	Yes	
Metro (Nashville) Public Works	No	Yes	Yes	Yes	
Michigan DOT	No	Yes	No	Yes	
Missouri DOT	No	No	No	No	We consider progression and safety and make a decision on which to choose.
New Jersey DOT	No	No	No	No	New Jersey DOT generally does not use lead/lag due to driver confusion, but we will consider this operation based on all available engineering factors.
Oregon DOT	No	No	Yes	Yes	
PB	Yes	No	No	Yes	
Retired traffic Engineer - 35 + years	No	Yes	Yes	Yes	
Seattle Dept. Of Transportation	No	No	Yes	Yes	
SRF Consulting Group	No	No	Yes	Yes	Tight diamond interchanges, and to avoid opposing left turn interlock
Utah DOT	No	No	Yes	Yes	We use lead lag, however, do so with caution, due to the "max recall" effect it creates due to the phase being left of the barrier. We ensure that volumes (i.e. Translated into splits) are consistent each cycle to justify it.
Washington State DOT	Yes	No	No	No	
* Note: The numbers indicate the general policy and practice as:					
1 Does not use lead-lag phasing due to concern of driver confusion					
2 The sequence must be consistent all the time if lead-lag is used					
3 Use lead/lag for the benefit of progression (e.g., bandwidth)					
4 Use lead/lag for the purpose of minimizing queue spillover					
5 Other (specify)					

Q5: Select from the following conditions when protected/permited left-turn control is NOT allowed

Table C-5 Survey Responses on Conditions When Protected/Permitted Left-Turn Control Is Not Allowed

Organization	1*	2	3	4	5
Arizona DOT	45	3	2	Varies	
Charlotte Department of Transportation	50	2	1		
City of Milwaukee, DPW			1		Poor visibility of opposing traffic due to grade or other geometric considerations
City of Arlington, Texas		2 + median	1	Crash rate, not quantity	
City of Boulder, Colorado			2	More than 4/year or 6/two years may require time-of-day protected-only operation.	
City of Glendale, Arizona			2		Dual left-turn lanes may be permissive if the opposing through volume and opposing lanes are very minor (i.e. A driveway coming out of a minor commercial development or a seldom used residential roadway)
City of Kennewick, Washington					We do not have specific conditions for not using permitted only, P/P, or protected only.
City of Little Rock, Arkansas					Utilize engineering judgment, check specifics of the accident problem vs. Capacity issues.
City of Rancho Cucamonga, California	45	2	1		Significant number of left turn crashes with P/PLT control - we then revert to protected only.
City of Toronto Transportation Services	79 km/hr (50 Mph approximately)		1		
City of Tucson, Arizona					If the sight distance is available then P/P is used. The factors of approach speed, number of lanes etc is NOT applicable to urban operations.
City of Wilmington, North California	50	3			
Harris County Public Infrastructure Department			1		Allowed only at "T" intersections with good sight distance
Iteris					When left turners cannot see clearly past opposing left turners.
Kimley-Horn			1		Sight distance is poor, very high cross product
Kentucky Transportation Cabinet		3	2	4/twelve months, 6/24 months, 8/36 months	
Louisiana Department of Transportation and				4/year	

Development					
Louisiana DOTD		3	1		
Maryland State Highway Administration	55	3	2		
Metro (Nashville) Public Works		2			
Michigan DOT	If speed limit is over 45mph, further review is needed but could still be allowed	2	1	6/year	Sight distance
Missouri DOT	45	3	1	5/year	Sight distance
New Jersey DOT		2	1		
Oregon DOT	45	3	1	3/year	
Seattle Dept. Of Transportation				3/year	
SRF Consulting Group	45		2		Wide medians where there are sight distance issues and left turn interlock issues
Utah DOT	50	3			I would say generally 3 through lanes and speeds 50 mph or more, however, we this may vary on engineering judgment.
<p>* Note: The numbers indicate the conditions as:</p> <p>1 Speed is greater than a threshold (e.g., 40 mph) (specify the speed)</p> <p>2 The number of through lanes is greater than a threshold (e.g., more than 2 lanes) (specify the number of lanes)</p> <p>3 The number of left-turn lanes is greater than a threshold (e.g., more than 1 lane) (specify the number of lanes)</p> <p>4 The number of crashes is greater than a threshold? (specify the number of crashes)</p> <p>5 Other (specify)</p>					

Q6: What other factors do you think important while determining left-turn control types that are not being included in the current guidelines?

Table C-6 Survey Responses on Other Factors that are not Included in Current Guidelines

Organization	Survey Responses
Caltrans	Agency preference.
Charlotte Department of Transportation	Sight distance
City of Arlington, Texas	Driver expectation - if used area wide constraints should not be as tight.
City of Boulder, Colorado	More emphasis on making decisions and implementing control types on a time-of-day basis.
City of Glendale, Arizona	The capacity reduction to through movements when left-turn control is added. Additionally, 3rd car detection (only bringing up an arrow when 3 cars or more are present) is very efficient in that more green time can be given to the through movement when the left-turn arrow isn't really needed.

City of Kennewick, Washington	Sight distance between left-turning driver and oncoming traffic. Conflicting pedestrian volumes. Intersection skew. We do not use the items in question 6 as conditions, only as items to be considered.
City of Little Rock, Arkansas	Left turn phasing should only be utilized when needed based on insufficient gaps in the opposing vehicle streams.
City of Toronto Transportation Services	Pedestrians and cyclists
City of Tucson, Arizona	Sight Distance for left turning vehicles. We run dual left turn lanes under P/P with and offset of the lanes to provide sight distance.
City of Wilmington, North California	Sight distance for left turning vehicles, I would be more likely to implement permitted on geometric offset left turns than on opposing left turns
Douglas County	Protected only induces more red light running, can cause overflow into thru lanes, increases delay during off peak, can cause increased rear-end accidents. Agencies would be more concerned with driver expectation instead of software.
Harris County Public Infrastructure Department	Traffic volumes and intersection geometry.
Louisiana Department of Transportation and Development	Capacity analysis to evaluate overall delay at the intersection. Do you have an exclusive left turn lane?
Louisiana DOTD	We have in house engineering directives to determine if protected left turn signal phasing should be installed. However, the type of left turn phasing is left to the individual traffic engineer as to what he or she would recommend at each particular intersection.
Metro (Nashville) Public Works	Approach sight distance (e.g. Hillcrests), width of intersection (if travel paths of opposing left turns come too close, lead-lag may be better)
Oregon DOT ¹	Type of display
Oregon DOT ²	Side street vs. mainline lefts. Detection is different, driver expectation is different, but DOT's guidelines do not differentiate
PB	Turning radius
Retired traffic Engineer - 35 + years	Many factors must be analyzed in each situation so it is not always possible to have absolute rules that must always be applied. Usually there are guidelines that say when a certain treatment will not be used, but again these are only guidelines and will not substitute for good engineering judgment and design.
SRF Consulting Group	Off peak operation. We have considered a tri-modal operation depending on volumes throughout the day. Permitted only, then protected/permitted and finally protected only. Our proposal was to use a five section head with a bi-modal LED red where the arrow and circular pixels are independently controlled. Red is circular for permitted and protected/permitted, red arrow for protected only.

Utah DOT	Cycle length and phasing compatibility with surrounding intersections. For example, if your corridor is two-phase intersections, adding left turn phases at an intersection kills the cycle length or leads to cycle length incompatibility. Also, it would be helpful to know when to go from single left to dual lefts. In addition, any guidelines should include the consequences and inefficiency of left turns because that is known to signal systems engineers, like myself, but not well known to some of the other traffic engineers.
Washington State DOT	There should be a MUTCD left turn warrant. The MUTCD should also tighten up on protected/permissive display configuration and operation (i.e. Flashing yellow during permissive operation)

Q7: Would you favor simple-to-use (less detail) guidelines, or guidelines that involve and/or incorporate specific intersection-level information (crashes, number of turn lanes, speed, number of opposing through lanes, cross-products, etc.)?

Table C-7 Survey Responses on Preferences for Guidelines

Organization	Type of Guidelines Preferred (simple-to-use or specific information?)
Arizona DOT	The specific intersection-level information works for ADOT.
Caltrans	Keep it simple.
Charlotte Department of Transportation	Intersection level information
City of Arlington, Texas	Specific guidelines
City of Boulder, Colorado	Specific information, if supported by solid research.
City of Glendale, Arizona	I favor simple-to-use guidelines, as engineering judgment is an important part of the evaluation that is not always captured by very specific guidelines.
City of Little Rock, Arkansas	I like guidelines that outline the factors that should be utilized. This will help traffic engineering officials determine need based on standard engineering principles utilized by other professionals.
City of Rancho Cucamonga, California	Existing guidelines work for us but if/when a specific type of P/PLT display is determined to best across the country, I would like to see specific standards and criteria developed supporting the accepted method.
City of Toronto Transportation Services	Specific but guidelines that is specific numbers, but generally the engineer should be able to apply judgment and document the reasons for not following the guideline.
City of Tucson, Arizona	Simple guidelines are best
City of Wilmington, North California	General guidelines since all locations are unique
Douglas County	Yes, using conflicting volumes & sight distance, taking into effect all impacts to traffic, not just the left turning traffic (delay, capacity, red light running, etc)
Harris County Public Infrastructure Department	If and when we go to protected/permitted displays other than at "T" intersections, we plan to come up with some internal guidelines similar to those mentioned in the question. Traffic volumes along with the geometry of the intersection will be a significant factor in helping us making this determination. Good progression and avoidance of the "trap" condition will

	also be a must.
Iteris	Supportable warrants for protected left turns would be helpful to the industry, but I think the use of permissive left turns is closely tied to local practice and will defy a consistent national standard without severe imposition on some locations.
Kimley-Horn	Specific guidelines but with a lot of flexibility for designer
Kentucky Transportation Cabinet	Specific intersection-level information.
Louisiana Department of Transportation and Development	Specific intersection-level information.
Louisiana DOTD	I would favor guidelines that incorporate specific intersection-level information.
Metro (Nashville) Public Works	The guidelines are easy to use but a spreadsheet or worksheet application would be nice.
New Jersey DOT	My preference is the simple-to-use guidelines. Each request needs to be evaluated on its own merits, since each intersection is different.
Oregon DOT ¹	Yes although there needs to be significant room left for judgment.
Oregon DOT ²	Specific intersection-level information
PB	Simple-to-use
Retired traffic Engineer - 35 + years	Guidelines that involve intersection specific information.
Seattle Dept. Of Transportation	General Simple-to-use guidelines
SRF Consulting Group	No each situation is unique. That is why we are engineers.
Utah DOT	Either or.
Washington State DOT	I would prefer more detailed guidelines with explanations and reasoning behind each guideline.

Several questions were asked whether there are any issues involved with those agencies and organizations that have already implemented or are planning to implement the new Flashing-Yellow-Arrow (FYA) display for protected/permissive left-turn controls.

Q8: FYA Implementation

Table C-8 Time of Implementation, Sites and Cabinet

Organization	Time of first implementation (month/year):	How many intersections:	Total number of intersection approaches:	Cabinet Type:
Charlotte Department of Transportation	Oct 2004	1	1	NEMA TS2
City of Boulder, Colorado	May 2004	2	6	332
City of Kennewick, Washington	Dec 2004	4	12	NEMA TS2
City of Wilmington, North California	Nov 2005	1	4	NEMA TS1
Douglas County	Summer 2006	Unknown now		
Louisiana Department of Transportation and Development				NEMA TS1
Michigan DOT	Within the next couple of years	1	4	
Missouri DOT	Summer 2006	5-Mar	Undetermined yet	NEMA
Oregon DOT	2004	8	17	332

Table C-9 Controller and Other Issues

Organization	Controller Make and Model:	Conflict Monitor Make and Model:	Do you use special external logic:	Do you use special external hardware (relay, etc.):	Do you use protected-permitted lead-lag operation at any intersections with FYA?
Charlotte Department of Transportation	Econolite ASC/2	Econolite	No	Yes, relays	Yes
City of Boulder, Colorado	Econolite 2070	EDI 2010	No	No	Yes
City of Kennewick, Washington	2070 ATC configured to NEMA TS2 Type 1 and Econolite ASC/3	Eberle Design Inc., EDI MMU-16LE smartmonitor	No	No	Yes - all 4
City of Wilmington, North California	Traconex TMP 390	SSS Guardian 12	Yes	Yes	Not yet
Douglas County					
Louisiana Department of Transportation and Development	Naztec 900 series and TS2	Naztec			
Michigan DOT					
Missouri DOT	Eagle M50		No		
Oregon DOT ¹	170E, HC11	Don't know	Yes	No	Yes
Oregon DOT ²	170E or HC11	Standard 16 channels	No, just long command box	No.	Not yet, but we may soon.

Q9: What happens when there is an emergency pre-empt?

Table C-10 Survey Responses on Emergency Pre-empt

Organization	Survey responses
Charlotte Department of Transportation	Do not have it here.
City of Boulder, Colorado	Emergency vehicles receive a directional pre-empt (green arrow plus green ball), opposing left-turn has flashing yellow arrow.
City of Kennewick, Washington	With current MUTCD P/P operation the signal cycles to green for the preempt direction with concurrent green for the opposing direction. We do not provide a green arrow to avoid the yellow trap. For FYA we currently are doing the same operation, however, we are looking at allowing green arrow/ball for the preempted approach.
City of Wilmington, North California	no preemption
Oregon DOT	It acts normally except when the FYA is already up in which case the FYA opposing the EV phase would stay FYA
Retired traffic Engineer - 35 + years	Normally a leading left turn is provided along with the through movement in the direction in which the emergency vehicle is proceeding.

Q10: What does the local first response agencies think of this operation?

Table C-11 Survey Responses on Local First Response Agencies Feedback

Organization	Survey responses
Charlotte Department of Transportation	No feedback.
City of Boulder, Colorado	Very limited feedback. Some inquiry as to reason for doing something different.
City of Kennewick, Washington	No issues
City of Wilmington, North California	Police indicate a perceived driver confusion, however only two citizen calls on the location, both agreed that FYA was better when concept was explained
Oregon DOT	Have not had any complaints
Retired traffic Engineer - 35 + years	They like it most cases.

Q11: What, if any, public reactions have you received?

Table C-12 Survey Responses on Public Reactions

Organization	Survey responses
Charlotte Department of Transportation	None
City of Kennewick, Washington	Majority of drivers understand. When first implemented we had inquiries as to the operation. These have reduced significantly over time. Similar to our initial roundabout installations.
Oregon DOT	Mostly positive with some negative. One problem intersection involves high percentage of heavy trucks on a downgrade who abuse the FYA
Retired traffic Engineer - 35 + years	The public seems to understand and uses the preemption to get out of the way of the emergency vehicles or to at least help clear a path for it.

Q12: What, if any, public outreach has your agency provided?

Table C-13 Survey Responses on Public Outreach Provided by Agencies

Organization	Survey responses
City of Boulder, Colorado	Press releases when first implemented information on website.
City of Kennewick, Washington	Prior to and after implementation of FYA there were articles in the local newspaper and news reports on local TV/radio. Subsequent to the implementation there have been a few follow-up news reports done by the local TV stations.
City of Wilmington, North California	All Media, newspaper, radio, website, TV
Oregon DOT	Pamphlets available explaining the operation as well as description in the Drivers manual. FYA brochure available online, press release explaining FYA operation was made available to local newspapers. Press releases focus on the local intersection that is to be fitted with a FYA

Q13: Do you plan to install more of the FYA operation? If not, why?

Table C-14 Survey Responses on the Installation of More FYA Operations

Organization	Survey responses
Charlotte Department of Transportation	We will when it appears in the MUTCD.
City of Boulder, Colorado	Probably, pending updating crash information.
City of Kennewick, Washington	Have recently been notified that the City will be getting a safety grant to change out all of our current signals that employ the 5-section MUTCD standard configuration to FYA. This change out should occur in 2007/08.
City of Wilmington, North California	Yes
Oregon DOT	Yes. It is OREGON DOT's standard for protected-permissive displays.
Retired traffic Engineer - 35 + years	Unknown at this time

Q14: Based on your observation or based on actual crash reports, what has happened to the crash frequency and type of crashes?

Table C-16 Survey Responses on Crash Trend after Implementation of FYA Operations

Organization	Survey responses
Charlotte Department of Transportation	Remained the same.
City of Boulder, Colorado	No issue at one location: no crashes before, no crashes after. Mixed results at other, busier location with lead/lag operation. Existing accident problem has declined so far in lagging direction. Accidents have increased in leading direction, possibly in part because it went from protected-only lead/lag operation to protected-permitted w/ the FYA.
City of Kennewick, Washington	Two intersections went from permitted only to FYA and two from standard MUTCD P/P to FYA. The latter two were only done recently, so too soon to tell crash results. The first two have been in operation over one year, however, besides going from permitted only to FYA there were other significant changes at these intersections that necessitated the signal operational changes, therefore making comparisons between the before and after conditions can not be made.
City of Wilmington,	no crashes since implementation, but not statistically significant time period.

North California	
Oregon DOT ¹	It is too soon to tell
Oregon DOT ²	When used in place of a doghouse, they are safer, i.e. fewer crashes.
Retired traffic Engineer - 35 + years	Accidents of ten increases when protected/permissive operation is used especially if replaces protected only operation at a location. Left turn crashes are usually sharply reduced when any kind of left turn protection is introduced at a location where there was only permissive control provided previously.

Q15: Other comments:

Table C-17 Other Comments from the Survey Responses

Organization	Other comments
Caltrans	At Caltrans, left turn pockets will be provided at all high speed highways. If it is signalized, left turn is controlled by protected only phase. This is different from local agencies in California. We use Caltrans Traffic Manual, which is now California MUTCD supplement (no completely done yet). We have another design guideline, which is based on the Green Book method (Harmlink chart for left turn lane installation).
City of Milwaukee, DPW, Wisconsin	Do not plan to implement flashing yellow arrow display. Common sense and the analysis of interacting elements need to be considered when installing the appropriate left turn treatments. It is going to be difficult to establish an all-inclusive set of criteria for selection of appropriate left turn control.
City of Tucson, Arizona	For urban intersection under heavy traffic loading protected only operations are to be avoided under the regions congestion management guidelines. "Signalized Intersections Informational Guide" by FHWA--FHWA-HRT-04-091 demonstrated the operational and safety benefits of P/P dual left turn lanes. p319.
Harris County Public Infrastructure Department	I think the FYA can be a viable way to be able to change from protected-only to protected-permitted by time-of-day, while avoiding the trap condition and the need for louvers as with the Arlington phasing, but I do have two concerns with the proposal that would prevent me from ever using this type of head control in my jurisdiction. 1 - The original proposal had the flashing amber arrow and the clearance to the flashing amber arrow in the same section (second from bottom). There MUST be a position change to make it clear that the phase is now in its clearance interval. Motorists tend to not immediately notice the change from flashing operation to steady operation, without a position change. Not sure if this has been addressed. 2 - The second indication from the top is another amber arrow which should be used to clear the permissive interval (flashing amber arrow) and address concern #1 above (with the position change). However if this is used to clear a permissive interval there is technically a conflict with the opposing direction which would have a yellow ball indication facing a steady amber arrow indication. Hence the arrows would have different meanings depending on whether they are clearing a protected interval, or a permissive interval. This is not a good thing and can lead to issues down the road as we are technically changing the meanings of head controls that have been around

	<p>for years. Hence, we feel that the amber arrow (2nd from the top) should be replaced with an amber ball to make it clear that this is the end of a permissive interval. The amber arrow (2nd from the bottom) would serve as the flashing amber arrow and the clearance from the protected green arrow. No matter what the case there would always be a position change. If these issues aren't addressed or continually downplayed, I don't see this making it very far due to liability issues.</p>
Iteris	<p>My experience is based on being in charge of the signal operations at the City of Austin, the City of San Antonio, and as while at Texas DOT and as consultant primarily in Texas. I have not made these decisions since the recent research promoting the use of the flashing yellow arrow.</p> <p>The ranking of the factors will change by situation. In reality, all the decisions were made by balancing those factors, with no clear priority between them.</p>
Kentucky Transportation Cabinet	<p>Some of our engineers are interested in using FYA. Some feel there will be a benefit in signal head arrangement especially as left-turn lanes with positive offset are encouraged. Others are reluctant to try it. At the present time, we do not have support to try it.</p> <p>We have a traffic signal phasing policy which addresses many of the issues that we consider when determining what type of left-turn phasing is used. A copy can be provided if requested.</p> <p>Our policy is based on a Kentucky Transportation Center report entitled (Guidelines for the Installation of Left-turn Phasing). A copy of this report should be available on their website.</p>
Louisiana Department of Transportation and Development	<p>The Department currently has not implemented the FYA as this has not been approved by the MUTCD. I serve on the MUTCD Traffic Signal Committee for Chapter 4D. This will go to sponsors in June 2006. Hopefully it will be approved for the 2008 edition. In order to use FYA you must currently apply to FHWA.</p>
Maryland State Highway Administration	<p>We think there are problems with the FYA operation. Namely, the solid Yellow arrow in the phasing sequence comes up twice. Once it is protected and the other is not. This is a problem.</p>
Oregon DOT	<p>Oregon DOT still lacks software to allow easy setup of FYA timing. We are currently using long command box logic codes within the Waipiti software. We are in the process of testing and troubleshooting new Waipiti software that contains FYA settings.</p>
SRF Consulting Group	<p>In Minnesota we do not understand what the problem is with the current 5 section head and the sign "left on green must yield". We have not had any problems with driver comprehension, just bad gap selection. However, we have been using red arrow, yellow arrow, green arrow protected left turn signals since 1975 so our drivers know the difference between the two types of left turn situations. At permitted only locations, we do not put pedestals in medians with circular through indications, particularly if there are left turn lanes.</p>
SRF Consulting Group	<p>Seattle uses a flashing yellow ball for the permissive movement. Please forward a summary of the survey when it is available.</p>

List of Respondents

Name	Organization	Email	Telephone
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APPENDIX D: LEFT-TURN GUIDELINES FACTOR SCORING

The recommended scores for all the factors are included in this appendix. Each table describes a specific factor. A score is given to a particular type left-turn control based on the factor values. The sum of the three scores of each control type should be equal to 10. However, a 9.999 score is given to a particular control type if the other two scores are zero.

Left-turn Volume

Left-turn Volume, vph	Permitted	Protected/Permitted	Protected
<=60	9.999	0	0
<=100	8	2	0
<=200	5	5	0
<=300	3	6	1
<=400	0	5	5
<=500	0	2	8
<=600	0	1	9
<=700	0	0	9.999
>700	0	0	9.999

Volume Cross Product

Volume Cross Product	Permitted	Protected/Permitted	Protected
<=50,000	9.999	0	0
<=60,000	6	4	0
<=70,000	3	7	0
<=90,000	1	9	0
One Opposing Through Lane <=110,000	0	9	1
<=130,000	0	8	2
<=150,000	0	6	4
<=160,000	0	1	9
>160,000	0	0	9.999
<=100,000	9.999	0	0
<=140,000	6	4	0
<=180,000	3	7	0
<=220,000	1	9	0
Two Opposing Through Lanes <=240,000	0	9	1
<=280,000	0	8	2
<=300,000	0	6	4
<=320,000	0	1	9
>320,000	0	0	9.999

Number of Left-turn Lanes

Left-turn Lanes	Permitted	Protected/Permitted	Protected
1	3.333	3.333	3.333
2	0	3	7
3	0	0	10

Number of Through Lanes

Left-turn Lanes	Permitted	Protected/Permitted	Protected
0	0	0	10
1	3.333	3.333	3.333
2	3.333	3.333	3.333
3	0	3	7
4	0	0	10

Opposing Speed Limit

Speed, mph	Permitted	Protected/Permitted	Protected
15	3.333	3.333	3.333
25	3.333	3.333	3.333
30	3.333	3.333	3.333
35	3.333	3.333	3.333
40	3.333	3.333	3.333
45	0	3	7
50	0	2	8
55	0	1	9
60	0	0	9.999

Number of Left-turn Related Accidents

Accidents/Year	Permitted	Protected/Permitted	Protected
0	3.333	3.333	3.333
2	3.333	3.333	3.333
3	3.333	3.333	3.333
4	2	4	4
5	0	1	9
6	0	0	9.999
8	0	0	9.999
10	0	0	9.999

Combination of Number of Left-turn and Opposing Through Lanes

Left-turn Lane & Through Lane	Permitted	Protected/Permitted	Protected
11	3.333	3.333	3.333
12	2	4	4
13	0	3	7
14	0	0	9.999
21	0	2	8
22	0	0	9.999
23	0	0	9.999
24	0	0	9.999

Required Sight Distance

Speed, mph	Sight Distance, ft
20	160
25	200
30	245
35	285
40	325
45	385
50	445
55	540
60	635

Note: The sight distance shown above is calculated based on the maximum of the two values: the stopping sight distance and the sight distance required for drivers accepting a 5.5-sec critical gap. If the field sight distance does not satisfy the required sight distance shown in the table, a protected-only control must be selected.



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